IDA PAPER P-2153

MANAGEMENT OF RISK AND UNCERTAINTY IN PRODUCT DEVELOPMENT PROCESSES

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June 1989

Prepared for
Office of the Under Secretary of Defense for Acquisition
(Research and Advanced Technology)

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1801 N. Beauregard Street, Alexandria, Virginia 22311-1772

IDA Log No. HQ 88-33819

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY
DD Form 254 dated 1 October 1983

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE
Not Applicable

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
IDA Paper P-2153

5. MONITORING ORGANIZATION REPORT NUMBER (S)

6a. NAME OF PERFORMING ORGANIZATION
Institute for Defense Analyses

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
OSD, OUSD(A), DoD-IDA Management Office

6b. ADDRESS (CITY, STATE, AND ZIP CODE)
1801 North Beauregard Street
Alexandria, Virginia 22311

7b. ADDRESS (CITY, STATE, AND ZIP CODE)
1801 North Beauregard Street
Alexandria, Virginia 22311

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
OUSD(A), R&AT/ET

8b. OFFICE SYMBOL

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
MDA 903 89 C 0003

8c. ADDRESS (City, State, and Zip Code)
The Pentagon, Rm. 3D1089
Washington, DC 20301-3080

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT	PROJECT NO.	TASK NO.	ACCESSION NO. WORK UNIT
		T-D6-553	

11. TITLE (Include Security Classification)

MANAGEMENT OF RISK AND UNCERTAINTY IN PRODUCT DEVELOPMENT PROCESSES

12. PERSONAL AUTHOR(S).
Edison Tse, Stanford University, and William E. Cralley

13. TYPE OF REPORT	13b. TIME COVERED FROM	TO	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	4/88	9/88	June 1989	95

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Concurrent Engineering, Simultaneous Engineering, Engineering Management, Risk, Uncertainty, Overlapping Development Process, Quality, Life Cycle Cost, Unified Life Cycle Engineering, Taguchi Methods, Loss Function, Decision Support Systems

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
The goal of the Unified Life Cycle Engineering (ULCE) program is to develop enhanced design environments that will allow supportability and producibility to be considered early in the product design cycle along with the usual factors of cost, performance, and schedule. This paper considers the engineering management aspects of one approach to ULCE: an overlapping development process in which technology development, design, manufacturing process planning, and support process planning are conducted in parallel. Such a process, commonly called concurrent engineering, has shown considerable promise in commercial industry in reducing development lead time, reducing product cost, and improving quality. However, such a process also requires much more careful management due to the increased risk and uncertainties which result from the incomplete information transfers which must of necessity occur between the teams performing the different phases of the development. This paper presents an analytical approach to management of overlapping development processes in the face of such risks and uncertainties. The approach taken is similar to that of Taguchi in that a key aspect of the method is the development of a loss function which is used to gauge the relative undesirability of various courses of action in the development process.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS REPORT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22C. OFFICE SYMBOL

DD FORM 1473, 84 MAR

C.S. 6-16-89

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

IDA PAPER P-2153

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INSTITUTE FOR DEFENSE ANALYSES

Contract MDA 903 89 C 0003
Task T-D6-553

PREFACE

This report was prepared by the Institute for Defense Analyses (IDA) for the Office of Engineering Technology, Deputy Under Secretary of Defense (Research and Advanced Technology), and the Air Force Human Resources Laboratory under Contract Number MDA 803 89 C 0003, Task Order T-D6-553, "Applications of Systems Engineering Techniques to Development of an Unified Life Cycle Engineering Environment."

The issuance of this report satisfies subtask (4): "Investigate methods of structuring a design process which will allow for a measure of robustness in that process in the face of uncertain change in design requirements or unforeseen circumstances arising in the course of the design."

This paper was reviewed by Drs. Frederick R. Riddell and James Pennell of IDA and by Professor Daniel P. Schrage of the Georgia Institute of Technology, a consultant to IDA.

CONTENTS

FIGURES

EXECUTIVE SUMMARY

A. BACKGROUND

Unified Life Cycle Engineering (ULCE) is an Air Force Project Forecast II R&D Initiative whose goal is development of:

> A design engineering environment in which computer-aided design technology is used to continually assess and improve the quality of a product during the active design phases as well as throughout its entire life cycle by integrating and optimizing design attributes for producibility and supportability with design attributes for performance, cost, and schedule. [Ref. 1]

In 1986, IDA was requested to analyze the requirements for decision support to support an ULCE design process. The results of that analysis indicated that planning and management of the design process (meta-design) are key factors in successfully implementing ULCE. This report contains the results of a follow-on effort to IDA's initial work on architecture and integration requirements for ULCE in which we address the problem of uncertainty in product development--how to quantify it, manage it, and make good design decisions in its presence.

B. UNCERTAINTY AND RISK IN PRODUCT DEVELOPMENT

Uncertainties come in various forms in product development. The design team faces both upstream and downstream uncertainties. Upstream uncertainties include, for example, uncertainty in the specification of design requirements. This uncertainty relates to the possibility of modification of the original specification that they are designing to. Such changes occur frequently in weapon systems procurements and can cause havoc in the design process. Downstream uncertainties may reflect a lack of knowledge as to the environment in which the product will be used or uncertainties in future availability of spare parts. Uncertainties in manufacturing processes, such as process variability, are also examples of downstream uncertainties from a design standpoint.

Another class of uncertainties pertains to processes in which there are parallel efforts being conducted that must come together at some point to develop the total product. One example of this is when both a design and an R&D activity are being pursued in parallel, with the design team assuming that the R&D activity will be able to develop a new technology needed by the designers at a certain time. The designers should consider that the actual time of availability of the new technology is uncertain, and should structure their activities accordingly. Entire design approaches have been scrapped after much work because a critical technology did not materialize when it was needed and the designers had not taken the uncertainty of the technology's availability into account.

Clearly, if we are to consider uncertainties in the product development process, we need a structured approach in which to do this. In this report, one such approach for management of uncertainty is presented. This approach is based on the paradigm of a loss function that is similar to that of Taguchi's parameter optimization methodology. [Ref. 4]

C. APPROACH TO HANDLING UNCERTAINTIES

The Taguchi method of parameter design is a method for determining a set of design parameters that make the resulting design robust in the sense that its expected deviation (in the face of internal and external noise) from a set of target specifications, as measured by a loss function, is minimized. The Taguchi method is thus a design methodology structured toward handling of downstream uncertainties. In this paper we propose an approach that allows the product development team to address not only downstream but also upstream uncertainties and to balance the reduction of both types of uncertainty against the achievement of a low product life cycle cost.

This is accomplished through the development of a generalized loss function that incorporates not only variability but also life cycle cost. Once such a generalized loss function has been computed, it can be used to evaluate alternative design concepts from the standpoint of their robustness to deviations in requirements (i.e., upstream uncertainty). An approach, based on trading off expected loss versus risk of loss (variability of loss based on the upstream uncertainty distribution) has been developed, which allows evaluation of alternative design concepts and also provides guidance for altering the requirements in cases where such alterations may greatly reduce expected loss.

A design concept that is robust with respect to the design requirements is called a flexible design concept. Within such a concept, we can vary individual details in such a

way as to satisfy a variety of requirements. Without such flexibility, a change in requirements may necessitate going to a completely new design concept, with subsequent loss of a great deal of engineering manhours that have been expended on the old concept. Flexible design concepts thus offer lower risk in terms of increased robustness to changes in requirements. However, such a flexible concept may achieve a lower level of performance than more restrictive concepts. Thus a trade-off must be made based on one's relative preference for high performance versus low risk.

D. MANAGEMENT ISSUES

While uncertainties should be considered to some extent in all product development processes, processes in which there is a considerable degree of overlap in different phases, such as the concurrent design or simultaneous engineering approaches, require special attention by management to control of uncertainty and risk. This increased demand for management control arises from the greater uncertainties faced by members within each phase--the members have to deal with a large degree of ambiguity in their problem solving activities at the beginning. However, as time progresses, the ambiguity starts to decrease. When much ambiguity exists, the team members need to factor flexibility concepts into their activities, such as investigating alternative paths and building in buffers to allow for change. When the ambiguity has been reduced to some threshold level, the problem solving activities can then focus on considerations of optimization.

Such a problem solving process is analogous to the funnel process [Ref. 2], except in this case, we are dealing with the development of a specific product, rather than the selection of new ideas or innovations to be further developed and marketed. In the case of a design project, the degree of flexibility to be introduced in the beginning of the funnel process is directly proportional to the level of ambiguity the team members have to face in the beginning of the phase and inversely proportional to the cost of introducing such flexibility. A major management issue arises in controlling the shape of the funnel--the dynamic reduction in ambiguity over time.

E. CONCLUSIONS AND RECOMMENDATIONS

It should be emphasized that the research reported here is focused at providing a foundation that allows us to address ULCE properly from a risk perspective. Given competitive pressures, learning how to develop products using the most recent technology

in a timely manner to meet user needs, while keeping life cycle cost low is becoming increasingly important. This demands far more control in risk management throughout the process. Unfortunately, this issue has been rarely addressed in the vast array of research activities focused on product design and manufacturing.

Our contribution is a broad treatment of such issues and development of a foundation for further research activities. However, this report only provides a solution method at a conceptual level. To further develop the method into a practical tool, we must describe how to develop the response model, the model for the downstream uncertainties, and the optimization methods which will be required. In practice, the construction of such models is the major difficulty. In many cases, analytical form for such models may not be obtainable, which prohibits straightforward application of standard optimization methods.

Another difficulty lies in the assessment of uncertainties in deriving the loss function. Such assessment may be done by extracting experts' opinions in common situations or via a Monte Carlo simulation method. Different types of difficulties are associated with these two approaches--the first approach requires facing the issue of converting expert knowledge into an appropriate distribution; the second problem requires facing the issue of choosing the right level of model aggregation with an appropriate model error representation.

Recommendations for specific research areas that need attention are described in the following paragraphs.

1. Evaluation of the Generalized Loss Function

In this research, we have developed the concept of the generalized loss function, which balances life cycle cost with quality lost due to deviation from target values (variability). Such a function would play a major role in the whole risk management process. Thus the success or failure of implementing the method discussed in this paper hinges on being able to derive or approximate this function. This computation involves solving two optimization problems, as outlined in Chapter IV. Research on a methodology to solve these optimization problems, which in many situations cannot be represented in analytical form, is needed.

2. Assessment of Requirements Ambiguity Based on Perceived Need

The next critical function that is needed to perform risk management is quantification of requirements ambiguity. This function is assessed in the beginning of the design process based on some unclear notions of how the product should be used. Note that this is not a statistical uncertainty but rather a reflection of the limits of our knowledge of how achieving certain requirements will meet the user's needs.

3. Design Concept Evaluation--Integrating Requirements Ambiguity and the Generalized Loss Function

While integrating requirements ambiguity and the generalized loss function is, conceptually, rather straightforward (as described in Chapter IV), practical implementation is difficult. Note that the integration hinges on generating the requirements uncertainty distribution as well as the generalized loss function. When the input requirements space is a continuous parameter set, the generation of these two functions for all parameters will be totally impractical. We need a methodology to allow us to approximately evaluate design concepts without requiring us to evaluate requirements uncertainty and the loss function over such a continuous parameter set.

4. Managing the Dynamic Reduction of Upstream Ambiguity

One cycle of the downstream and upstream integration will result in either a reduction of requirements ambiguity or identification of a potential conflict situation. The management issues are how to further reduce the requirements ambiguity in the first situation and how to resolve conflict when the second situation arises. The solution for both management issues hinges on exploring the effective use of resources to carry out certain activities that will modify or refine the assessments of requirements uncertainty and the generalized loss function.

The manager must choose from a host of options to continue the reduction of requirements uncertainties in some optimum manner or try to resolve potential conflicts. Each of these activities requires resources of dollars, man-hours, and time. Thus the problem is one of resource allocation so that

- The project can be finished "on time,"
- The development cost is within budget, and
- The available resources are optimally used.

This resource allocation problem is non-standard since all possible options are not specified a priori. Rather, the generation of new options may result from an assessment of the solution of an old resource allocation problem and exploring how combinations of certain activities will influence the requirements uncertainty and loss function.

5. Demonstration of Applicability of the Methodology to Specific Classes of Problems via Real Cases

Since the development process and the method proposed in this paper are different from conventional practice, before one can develop some of the heuristics discussed in this paper, one needs to accumulate working experiences by applying the methodology to specific classes of product development problems. Another objective of such application is to demonstrate the usefulness of the methodology. We propose that real application cases, which by themselves are topics of significant importance, be considered for evaluation of this methodology.

Some of these potential application areas include managing the contracting process, product identification and development, concurrent engineering in high technology product development, and planning of a Science and Technology (S&T) Program in conjunction with advanced weapon system development.

6. ULCE Decision Support Environment

To support the ULCE implementation process, we need to develop an ULCE environment that can support the manager in controlling dynamic reduction in requirements ambiguity and the functional groups in integrating the downstream and upstream analysis process when a specific ambiguity level is provided by the manager. Individual decision support systems are currently being developed for supporting certain specific functional group activities [e.g., computer-aided design (CAD)/computer-aided manufacturing (CAM)]. It is impractical to ignore all the existing systems and redevelop a new ULCE environment from scratch. Therefore, research on how to integrate and evolve the current systems to the target ULCE environment is the major challenge. We believe that this requires, first, a thorough understanding of the workings of the overlapping process as well as how the management issues arising from such processes can be addressed and solved effectively before the proper ULCE decision support environment can be designed.

I. INTRODUCTION

A. BACKGROUND

Unified Life Cycle Engineering (ULCE) is an Air Force Project Forecast II R&D Initiative whose goal is development of

> A design engineering environment in which computer-aided design technology is used to continually assess and improve the quality of a product during the active design phases as well as throughout its entire life cycle by integrating and optimizing design attributes for producibility and supportability with design attributes for performance, cost, and schedule. [Ref. 1]

In view of the recognition that design decisionmaking is a key element of any successful approach to ULCE, the Air Force in 1986 requested that the Institute for Defense Analyses (IDA) identify requirements and issues related to design decision support that should be addressed by the Air Force through additional research and development activities. In response, IDA formed a working group of individuals from industry, academia, and government to address this question. This working group recommended, among other things, that applications of systems engineering techniques and tools be considered in the structuring of ULCE itself. The design and development process is itself a system whose inputs are perceived user needs and whose output is a weapon system designed to meet those needs. As a follow-on to this recommendation, the Air Force requested that IDA conduct a study of systems engineering methodologies, identifying various ways that such methodologies could be applied to ULCE development. This report constitutes a portion of IDA's response to this request.

B. APPROACHES TO UNIFIED LIFE CYCLE ENGINEERING

The primary focus of the ULCE program has been on applications of computer-aided design (CAD) technology to improve the way weapons are designed. In particular, the Air Force RAMCAD (reliability, availability, and maintainability through computer-aided design) development program, which is one of the ULCE core programs, seeks to

integrate reliability, maintainability, and supportability (R,M&S) analysis tools with a CAD system to facilitate rapid analysis and turnaround in evaluation of designs from an R,M&S viewpoint. Such capabilities will allow designs to be influenced from an R,M&S standpoint during the active design phase, when there is still enough flexibility to allow for changes. This is a simple example of how designs can be improved by making information about the effect of the designer's decisions on some downstream characteristic available to the designer during design creation.

The logical extension of the RAMCAD approach leads to development of intelligent CAD systems linked to knowledge-based systems with the ability to reason through the implications of each design decision with regard to all downstream factors such as manufacturability, cost, safety, reliability, and maintainability and to return advice and information to the designer on not only the implications of his decision but also alternative courses of action that might be considered. This approach appears to be feasible as long as we are working in an area where the number of alternative decisions and possible implications of such decisions are small enough to make development of a rule base feasible.

As we move to higher levels of complexity in a modern weapon system, however, detailed tracking of all the possible implications of each decision throughout the hierarchy and through all of the downstream processes quickly becomes very difficult. It is at this point that we must begin to take a systems view of the design process and recognize that decisions must be made without complete information on all of their implications. Moreover, the inputs upon which decisions are made are also subject to change as we proceed through the design process. Thus if we are to develop an ULCE system that handles the total design process for a complex weapon system, we must address issues of management of the design process in the face of uncertainties of various sorts.

C. MANAGEMENT OF RISK AND UNCERTAINTY

Risk and uncertainty enter the development process from a variety of sources. At the beginning of the process, a set of requirements and specifications for the product to be developed must be supplied to the design team. During the course of the design effort, changes in these specifications are often necessary. Such changes can result in redesign efforts, the cost of which increases exponentially as they are undertaken later and later in the development process.

In the case of modern weapon systems, in which state-of-the-art performance is required, we also have significant technological risks to contend with. To meet the performance requirements, a new technology may be required. There will be uncertainty about whether such technology is possible, and, if possible, when it will be available. Delays in availability of particular technologies may lead to schedule slippage and cost overruns when alternative design concepts must be adopted in the absence of the required technology.

Risks and uncertainties also arise from downstream considerations. There may be considerable uncertainty regarding the ability of available manufacturing processes to produce the design within acceptable tolerances. There may also be uncertainties regarding the usage environment for the weapon system once it is deployed. Other uncertainties include such things as parts availability and the availability of sufficiently skilled personnel to operate and maintain the system when it is finally deployed.

Management and structuring of the development process in such a way as to properly cope with these risks and uncertainties is a key issue for ULCE. In this report, we examine some of the management problems inherent in various approaches to product development and offer an overall structure for attacking these problems. It is our view that the presence of uncertainties and risk must be openly acknowledged and explicitly dealt with in structuring and managing the product development process. Many current practices in design, for example, ignore the presence of uncertainties from both upstream and downstream sources. Such a practice contributes significantly to failure to meet schedule constraints and increased development costs.

D. ORGANIZATION OF THE REPORT

This report contains a conceptual approach to management of risk and uncertainties in product development and illustrates this approach in various sample application examples.

In Chapter II, we examine alternative ways product development processes can be structured. In particular we contrast the serial approach with an overlapping approach, which is becoming popular with the adoption of concurrent design processes. We also identify issues related to the management of these processes.

In Chapter III, we consider a simple paradigm for managing uncertainties in a situation with two phases of a development. This case is simplified to allow the reader to grasp the essentials of our approach without being overwhelmed by excessive detail.

In Chapter IV, we consider the more complicated case of management of uncertainty from multiple sources. In particular, we consider the management, from a design standpoint, of both downstream uncertainties and upstream uncertainties. We have developed an approach that allows for designs to be optimized for not only minimal expected loss due to internal and external noises (as in the Taguchi approach [Ref. 4]), but also acceptable life cycle cost. We conclude this chapter with several example formulations of the approach for specific problems.

In Chapter V, we address the issue of decision support requirements for management of uncertainty and risk in product development. An architecture is presented for a hierarchically linked set of workstations for both management of the process and design and other technically oriented work by the development team members.

Finally, in Chapter VI, we summarize the results of this report and present conclusions and recommendations for future research.

II. PRODUCT DEVELOPMENT PROCESSES

A. INTRODUCTION

Product development is a risky proposition. In the beginning, the process is triggered by user needs and requirements, some of which may be rather vaguely stated. To see whether such needs can be fulfilled, we must have some expectation of what is technically feasible--what the realm of possibility is. The process of combining these needs and possibilities will result in a more concrete specification of functional requirements for the product. The design process is a problem solving process in which creativity and knowledge are applied to the construction of a physical object that satisfies such a functional requirements specification. Product development does not begin with design but actually starts with determination of needs and the development of functional specifications that we expect to be achievable with available technology. The total process, beginning with user needs and specification of functional requirements and through actual delivery of the first unit of the product to the customer, is referred to as the product development process.

The product development process is anything but deterministic. However, the conventional approach to product development takes little account of the uncertainties inherent in the problem. Determination of functional requirements, design, and manufacturing are treated as three disjointed subprocesses with output of one process serving as a deterministic input to the next process. Within each subprocess, stochastic variations, which are statistical in nature, are considered by methods such as statistical process control. The management of uncertainties between subprocesses is not well addressed. The focus of design and manufacturing is to develop a product meeting a set of functional requirements, which are themselves determined so as to achieve the needs of the product's user.

However, success in a product development process is not determined merely by meeting functional (i.e., performance) requirements but also by these additional attributes, both of which we desire to minimize:

- *Product Development Lead Time*: The total elapsed time for the completion of the product development process. This attribute measures how fast we can progress from user needs to the reality of satisfying those needs. In commercial and military environments, this is an important attribute that measures one's competitive advantage.
- *Product Life Cycle Cost:* The total cost incurred in design, manufacture, operation, and support of a product over its lifetime. While part of this cost is controlled directly in the product development process (design and manufacturing cost), the remainder (operations and support cost) is indirectly influenced by this process.

In spite of the importance of these attributes, they are not explicitly dealt with in many current product development activities. As a consequence, the current design process does little to control the proliferation of uncertainties that result in unanticipated increases in lead time and high life cycle costs. While statistically there may be favorable performance in some instances, more often performance in one or both of these measures is exceedingly unsatisfactory.

To have better control of these two attributes, they must be addressed on an equal footing with performance attributes. This is the primary motivation for the research reported here. We argue that to address the three issues (lead time, life cycle cost, and satisfaction of needs), we must develop a new process for product development and solve the associated management problems inherent in this new process.

B. CHARACTERIZATION OF PRODUCT DEVELOPMENT PROCESSES

In light of the preceding discussions, it is useful to characterize alternative product development processes by assigning a three-tuple of attributes to each process. This will result in each process p being assigned a point a_p = (LT, LCC, NC), where

LT = Product Development Lead Time

LCC = Product Life Cycle Cost

NC = A measure of failure in satisfying functional requirements.

Clearly, these three attributes are, in some sense, in conflict with each other. For example, lowering NC might necessitate a higher development cost and thus tend to increase our measure in the second dimension.

One might attempt to incorporate these three measures into a scalar index that represents the absolute measure of success. However, this is impractical, if not impossible, since these attributes relate to different desires of the user. The first reflects the desire to incorporate the most recent technological advancements into the product; the second attribute reflects the total cost of ownership of the product; while the third reflects the desire to buy the product for a specific need. Thus retaining the measure of success as a point in three dimensional space is best.

For a particular initial set of user needs, the set of all product development processes $\{p\} = P$, which result in a product satisfying these needs may be characterized by a subset of three-dimensional space:

$$A = \{a_p, p \in P\}$$

We say that process p_2 is dominated by p_1 if $a_{p_1} \leq a_{p_2}$, i.e., each component of a_{p_1} is less than or equal to the corresponding component of a_{p_2}. In this case, process p_1 is said to be uniformly better than process p_2. If, however, there are i and j such that

$$a_{p_1}^{(i)} \geq a_{p_2}^{(i)} \text{ but } a_{p_1}^{j} < a_{p_2}^{j}$$

then it is not clear which process is to be preferred.

Suppose we have a set of processes $\{p_1, p_2, ..., p_n\}$ which can be applied to develop a product satisfying the same requirements. If a_{p_i}, $i=1,...n$, can be computed, then we can define a frontier curve in the attribute space A, denoted by F, such that

(1) For all $a \in A$, there exists an $f \in F$ such that $f \leq a$.

(2) If $f \in F$ and there exists an $a \in A$ such that $a \leq f$, then $a = f$.

In a two-dimensional space, such a frontier curve is illustrated in Figure II-1.

Clearly, the best development process must have its attributes located on the frontier curve. More than one process may achieve this. The final selection from among the various bests is based on trade-offs among the attributes.

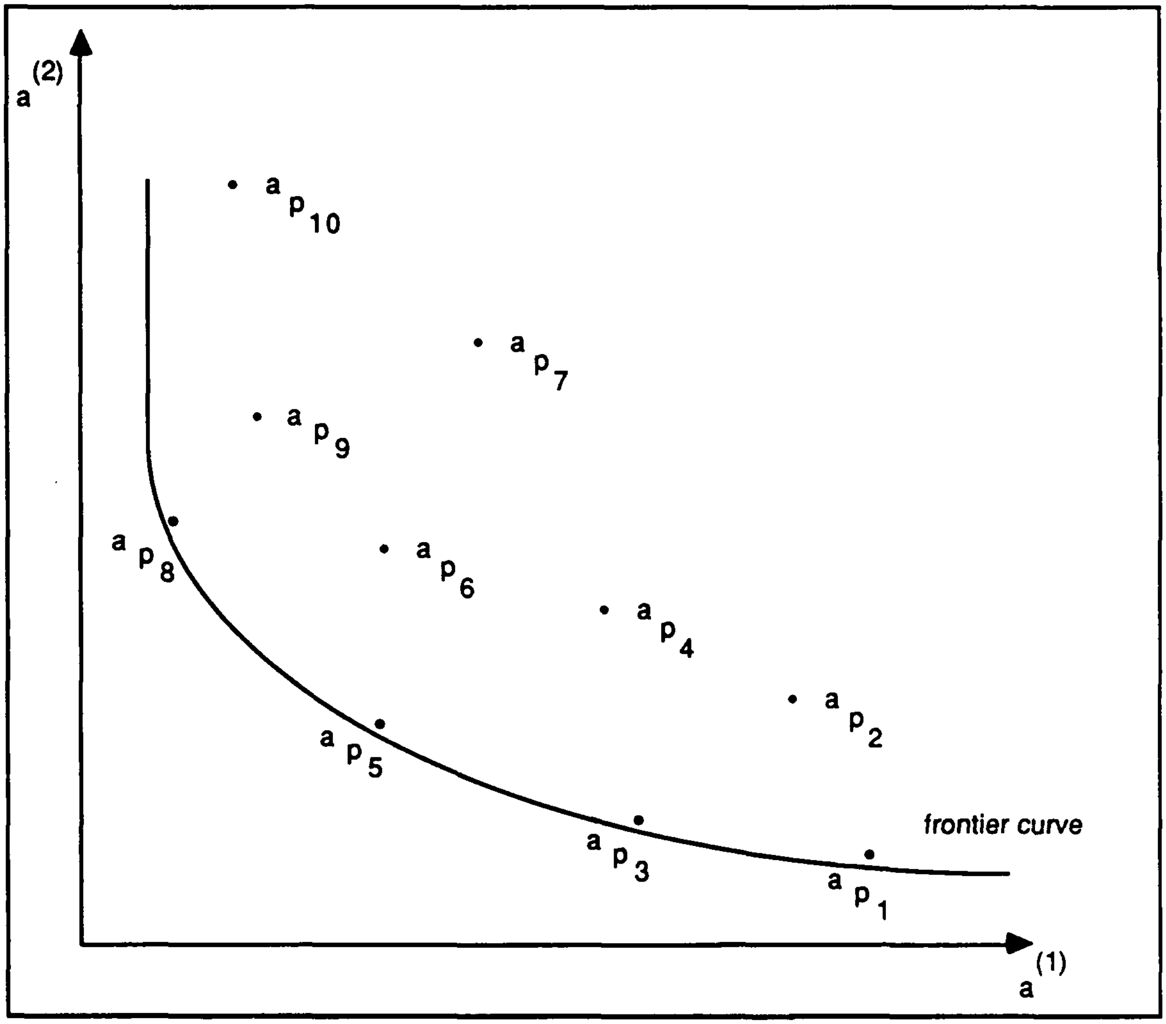


Figure II-1. Frontier Curve

In exploring alternate product development processes, the computation of the attribute measures associated with these processes may not be very accurate. However, considering these attributes up front will serve to bring out the major issues to be considered in choosing product development alternatives. Also, the notion of a frontier line guides us in making decisions within the development process in trading off one attribute with another when conflict exists.

C. ALTERNATIVE PRODUCT DEVELOPMENT PROCESSES

This section describes two fundamentally different classes of product development processes--serial approaches and overlapping (or concurrent) approaches. The issues of risk and uncertainty must be treated differently in each approach.

1. Serial Approach

This approach is practiced by many current product development projects, and has been essentially standard practice in the United States until recently. As such, it is also referred to as the conventional approach [Ref. 2]. In this approach, the development project is divided into phases, as illustrated in Figure II-2.

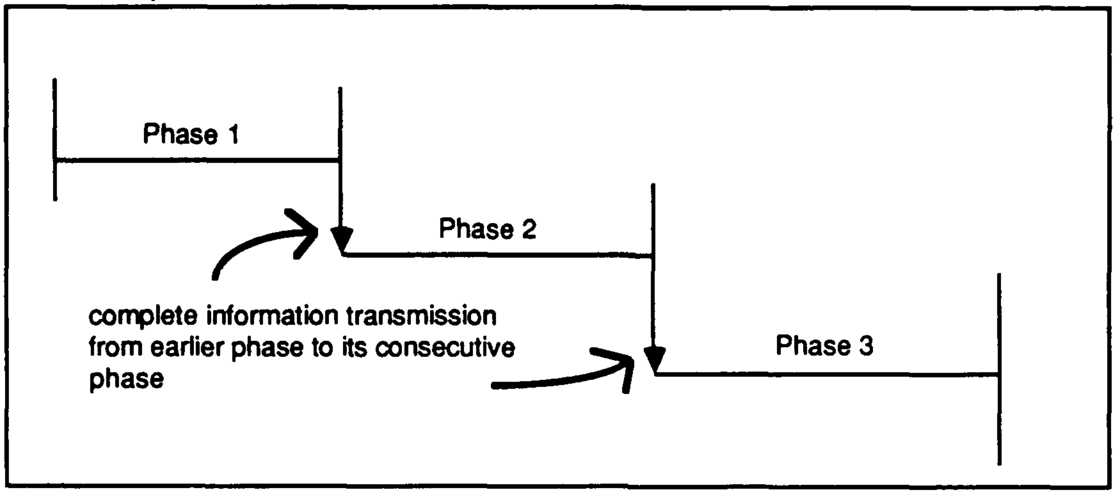


Figure II-2. Serial Approach

The characteristics of this approach are that

- A later phase is not begun until its preceding phase is complete.
- When a phase is concluded, a complete package of information is released to the next phase, which assumes this information as given (a fixed set of input data).
- If, however, conditions imposed by previous phases lead to difficulties in a later phase, the previous phases will be iterated until the difficulties are removed.

Potential difficulties that might be encountered using this approach include failure to meet functional requirements, violation of manufacturing constraints, or unacceptable production or support costs.

While the iterative process usually addresses the attainment of functional requirements directly, other attributes such as life cycle cost and development lead time are often left to chance. By the time problems are recognized in these areas, iteration to fix them is often too expensive or time consuming. Life cycle cost problems often do not surface until the development process is complete.

One way to reduce lead time attribute (and indirectly reduce life cycle cost) is to focus on reducing or eliminating iterative loops. To do this, in the earlier phases team members must be alerted when they are about to make a decision that will trigger an iterative loop in a later phase. This requires that the members participating in the early phase have full knowledge of how the downstream phases would be performed based on their decisions. A technological approach often advocated for providing this knowledge is development of a knowledge-based system that captures all of the problem solving knowledge in each phase. Thus when a member in an upstream phase is exploring an alternative, the knowledge-based system can be invoked to examine whether such an alternative will lead to downstream conditions that trigger an iterative loop.

An example of such a system would be a computerized model of the capabilities of the factory, which is made available in the design phase. With such a model, the designer could evaluate how the design drives production requirements and identify design features that adversely affect production costs. Another example is the generation of a knowledge base through processing of field failure data to provide the designer with the capability to flag design features that lead to higher support costs in the field.

While this technological approach sounds plausible, there are several drawbacks to such an approach. If the knowledge base does not contain enough information, many subtle situations will exist that cannot be handled. With the current state of technology, it is not clear whether an adequate knowledge-based system can be developed. Even if a sufficiently complete knowledge base could be built at reasonable cost (a highly questionable assumption), the static nature of such a knowledge base will limit its applicability in the modern environment where changes occur rapidly. To be useful, new insights must be captured fast enough for the knowledge-based system to be of help in problem solving. Maintaining such a knowledge base in a fast-paced, highly competitive development environment could be a very difficult and costly task.

2. Overlapping Approach

The overlapping approach is practiced by some of the more successful manufacturers. Studies on the characteristics and nature of such a problem solving approach have been conducted by researchers like Hayes, Wheelwright and Clark [Ref. 2]. The following paragraphs describe the characteristics of such an approach and discuss the management problems associated with such an approach.

In this approach, we allow the different phases to be overlapped as illustrated in Figure II-3. A distinguishing feature of such an approach is that when a downstream phase is carrying out a function in parallel with the upstream phase, information transmission is mostly one way (up to down) in the beginning, but then when the downstream phase picks up momentum, two-way communication will be established among the two phases' members.

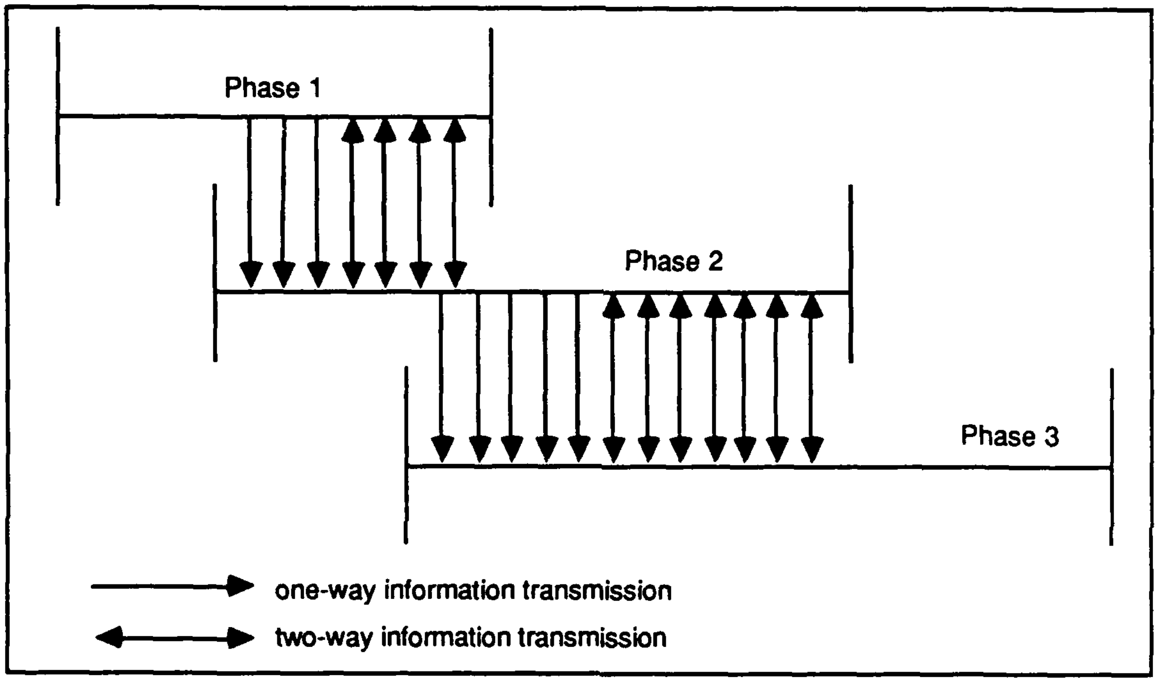


Figure II-3. Overlapping Approach

While the problem of the iterative loops between phases that occurs with the serial approach is resolved readily using the overlapping approach, a new set of problems are introduced. In the serial approach, a phase begins when the prior phase is completed; however, in the overlapping approach, the time when a phase can be started is su ·. management control. Note that each phase begins while the prior phase has not yet been completed, and thus each phase has to allow for contingencies due to uncertain inputs from the earlier phases. Similarly, earlier phases must be willing to release current solution proposals to later phases to see whether conflicts may arise. If conflicts arise, the members within the teams must resolve them in a cooperative manner. Thus, it is imperative that all team members in different phases know the overall objective or goal of the development project--what the product requirements and the relative trade-offs among the three attributes are.

Moreover, the ending of each phase is not well defined, but because of the overlapping nature, the official ending of each phase is not at all crucial. As long as conflicts can be resolved when they arise, one can assume that all phases end at the same time. For each phase, the activity intensity level might have a profile such as is given in Figure II-4. The coordination of the activity profile in each phase is a major management issue.

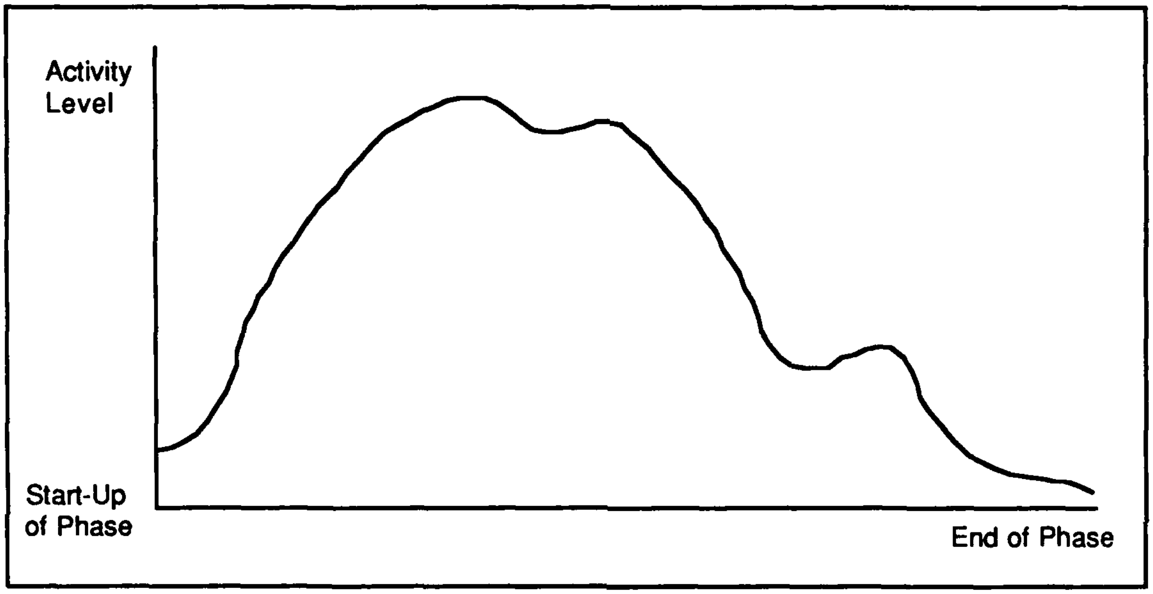


Figure II-4. Activity Profile Within a Phase Duration

The overlapping approach will greatly reduce iterative loops, but each individual phase may take a longer period of time to complete. The overlapping nature of the process and the reduction of iterative loops will, in general, lead to a shorter total development lead time, and the reduction of iterative loops will also result in a lower development cost. Bringing in downstream knowledge (e.g., manufacturability) will also improve the chances of reducing overall product life cycle cost. Therefore, to meet the same performance criterion, the overlapping approach should offer the opportunity to both reduce LT and reduce LCC. Thus all else being equal, we argue that a serial development process will be dominated by a well-managed overlapping development process--we emphasize well-managed because the overlapping process leads to a greater demand for management control.

D. MANAGEMENT ISSUES

The increased demand for management control arises from the greater uncertainties faced by members within each phase--the members have to deal with a large degree of ambiguity in their problem solving activities at the beginning. However, as time progresses, the ambiguity is reduced. When much ambiguity exists, the team members need to provide for flexibility in their activities, such as investigating alternative paths and building in buffers to allow for change. When the ambiguity has been reduced to some threshold level, problem solving activities can then be focused on considerations of optimization.

Such a problem solving process is analogous to the funnel process [Ref. 2], except in this case, we are dealing with the development of a specific product, rather than the selection of new ideas or innovations to be further developed and marketed. In the case of a design project, the degree of flexibility to be introduced in the beginning of the funnel process is directly proportional to the level of ambiguity the team members have to face in the beginning of the phase and inversely proportional to the cost of introducing such flexibility. A major management issue arises in controlling the shape of the funnel--the dynamic reduction in ambiguity over time.

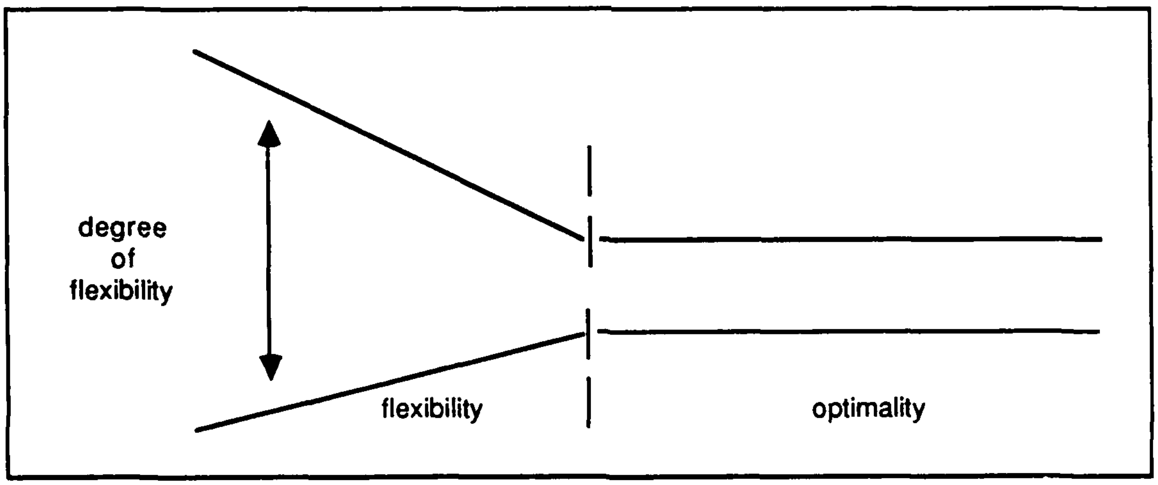


Figure II-5. Funnel Process

In the overlapping approach, control on the degree of flexibility, as time advances, is part of the problem solving activity. However, this is a team problem solving activity as opposed to an individual problem solving activity. The major issue here is communication among team members in different phases and resolution of conflicts among teams when they arise. Downstream members must provide critical review of a proposed decision that

is about to be made by the upstream members, regarding constraints that the decision may impose on their problem solving activities, which might seriously affect any of the three process attributes (LT, LCC, or NC). In addition, they may wish to provide suggestions, when appropriate, on variations of the proposed upstream decision that will lead to a uniformly better solution.

To facilitate addressing such management issues, we need to develop a more structured framework into which the problem can be cast for solution. The notions of risk and uncertainty must be more precisely defined and, to the extent possible, quantitative methods for management of risk developed. We begin such an undertaking in the next chapter, where we define basic concepts of risk and uncertainty and formulate a simple structure for dealing with these concepts.

III. BASIC CONCEPTS OF RISK AND RISK EVALUATION

A. TYPES OF RISK

The risks in product development can be broadly classified as market risk, development risk, and technology risk. Market risk refers to the risk that the product produced may not meet the market needs or capture significant market share. Development risk is the risk that the development project may take too long or be too costly. Technology risk is the risk that advanced technology cannot be successfully incorporated into the new product. The sources of these risks are different, yet they all influence the success of the product development project.

As an example of market risk, the design team may face the problem of upstream uncertainty in user requirements. The design team may start designing the product based on a set of requirements provided by marketing. Midway through the design, certain requirements may be modified. These changes could be of such magnitude that a total redesign of the product must be undertaken, resulting in significant schedule slippage and increased development cost, which could, in turn, cause a serious competitive disadvantage. To handle this problem, the members of the development team must recognize the uncertainty in requirements in the initial design phases and make provision for handling such uncertainty.

Development risk is related to the uncertain downstream effect of decisions made earlier in the development process. For example, the design team could specify a certain part in the design that could be built by the company or purchased from an outside vendor. Should the company choose to buy the part from a vendor, there is risk associated with the level of quality that the vendor can deliver and the continued existence of the vendor in the market. Adverse part quality could lead to a loss of future sales for the product developer. The business failure of a critical supplier could lead to significant costs due to loss of production capacity and significant start-up costs for providing for alternative sourcing.

To illustrate technology risk, consider a situation in which a new technology, under development by the R&D group, promises greatly improved product cost if incorporated into the product. The product design team may design the product in parallel with the activities of the R&D group, assuming that the technology will be available at a certain time. Also, the competitive situation may be such that achieving the planned product introduction time is critical. If the new technology does not become available as planned, the design team will be forced to go back to a conventional design that is not dependent on the new technology. The development schedule will likely slip and additional redesign costs will be incurred. Moreover, a significant market opportunity may be lost.

These above examples share certain common characteristics. Design decisions must be made in the face of uncertainties (upstream, downstream, or technological). A key problem in the design process is to maintain the risks at an acceptable level while optimizing expected product performance. Pure design optimization for performance, without explicit consideration of risk, can lead to disaster. Thus the success of a product development project depends on not only engineering creativity and knowledge but also management's capability to manage the risk in a dynamic manner. This chapter describes the fundamental concepts of risk management in product development and develops a systematic approach to deal with the problem.

B. RISK MANAGEMENT FOR TWO-STAGE PROCESSES

In this section a simple model for handling the management of uncertainty in processes with two phases is developed. Examples of such processes include product development with a specification team that communicates requirements to a design team, processes with parallel R&D and design efforts that must interact, and the portion of a development process that consists of the interactions of a design team with a manufacturing team. In the next chapter, process with more than two phases are considered.

The necessity of risk taking arises from the fact that we need to choose a specific course of action in the face of uncertainties. If these uncertainties cannot be reduced in time, then the choice of appropriate action can be based on statistical evaluation only. If the uncertainties can be reduced in the future, then one can either opt to wait until uncertainties are reduced to a threshold level before proceeding, or one can select a course of action while recognizing that uncertainties can be reduced or even eliminated in the future. In product development, if we choose to wait until uncertainties are reduced, we are

effectively choosing the serial process. If, however, we choose to proceed while recognizing that uncertainties may be reduced or eliminated, we are led to the overlapping process.

Let X_i be a specific option to be taken. Associated with X_i is a parameter set S_i which represents the restrictions on future options. If some event ε happens, then we can choose some $p \in S_i$ so as to optimize a certain objective. Let us single out cost as the objective in this case. Assume that we can develop a cost model (analytical or through simulation) $C_i(p,\varepsilon)$, $p \in S_i$. Then associated with the actual event ε, we will incur a cost that represents the resulting minimum cost if event ε actually occurs.

$$f_i(\varepsilon) \triangleq \min_{p \in S_i} C_i(p,\varepsilon) \tag{1}$$

Suppose that for each i=1,2....n, representing n different choices, we do not know what the actual event ε will be. We can evaluate $f_i(\varepsilon)$, i=1,...n as ε varies over a region. For n=2, possible plots are illustrated in Figure III-1. Now the question is whether X_1 or X_2 is the better option. The choice is clear if we know that $\varepsilon \in A$--X_1 is optimal. If, however, $\varepsilon \in B$, then the choice is less clear.

In some sense, choosing X_1 incurs a higher risk--if $\varepsilon \notin A$, but $\varepsilon \in B$, then choice of X_1 may lead to a disaster, whereas a choice of X_2 gives acceptable performance over a wider range. Thus the cost sensitivity, $f_i(\bullet)$, affects the risk associated with the decision X_i. However, the risk of choosing X_1 depends also on our assessment of where ε will lie. If we assess that $\varepsilon \in F$, where F is a proper subset of A, then choosing X_1 has no risk at all.

Let $\pi(\varepsilon)$ be a distribution of the exogenous event ε. We can calculate

$$\bar{f}_i \triangleq \int f_i(\varepsilon)\pi(\varepsilon)d\varepsilon \tag{2}$$

$$\sigma_i^2 = \int (f_i(\varepsilon) - \bar{f}_i)^2 \pi(\varepsilon)d\varepsilon \tag{3}$$

The risk associated with X_i is measured by σ_i^2. If σ_i^2 is large, then we may anticipate a big loss if a negative outcome occurs.

From (3), we note that σ_i^2 is dependent on the shape of $f_i(\varepsilon)$ as well as $\pi(\varepsilon)$. If $f_i(\varepsilon)$ is reasonably flat over a region of ε where $\pi(\varepsilon)$ is nonzero, then σ_i^2 is small. Thus risk can be controlled by selecting a specific option X_i, which results in a reasonably flat $f_i(\varepsilon)$ or by

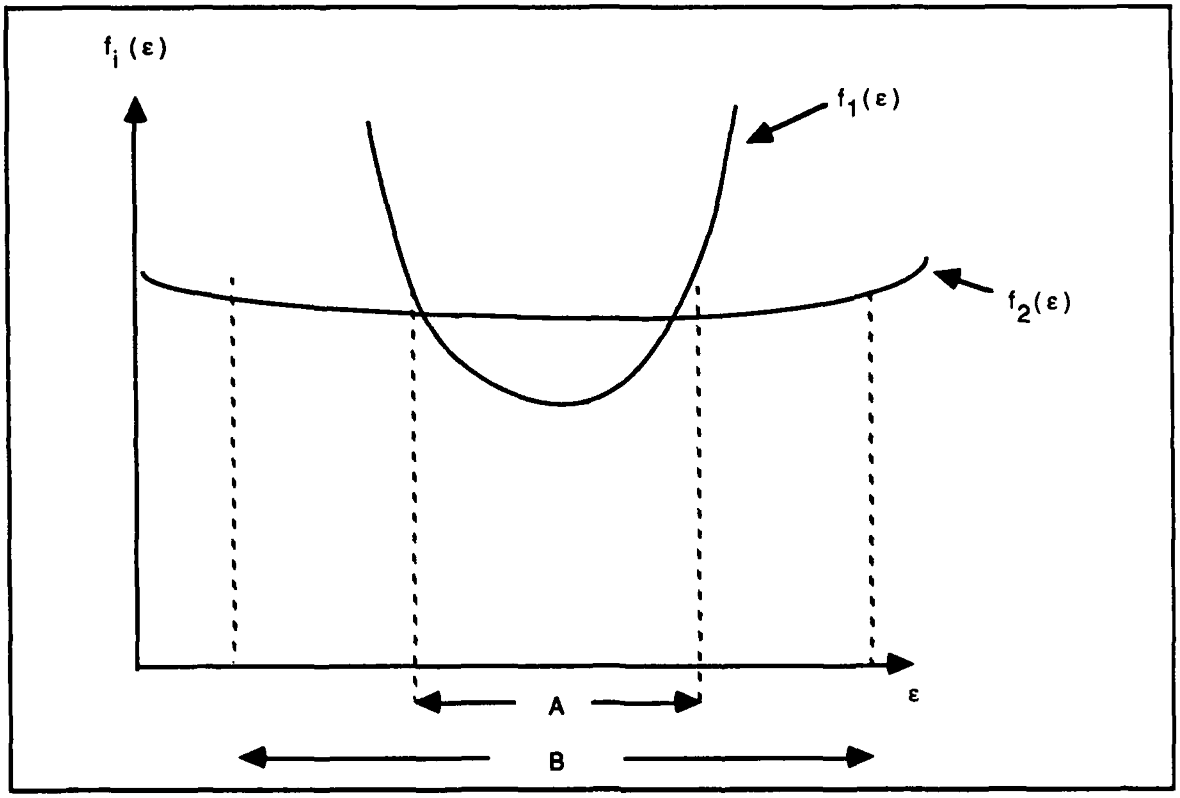


Figure III-1. Plots of $f_i(\varepsilon)$

controlling the distribution $\pi(\varepsilon)$. Usually, the selection of X_i that results in a flat $f_i(\varepsilon)$ will also yield a $f_i(\varepsilon)$ whose minimum $\min_{\varepsilon} f_i(\varepsilon)$ is reflectively high as compared to another option X_j, whose $f_j(\varepsilon)$ is not flat but

$$\min_{\varepsilon} f_j(\varepsilon) < \min_{\varepsilon} f_i(\varepsilon) \tag{4}$$

If $\pi(\varepsilon)$ is not controllable, then the trade-off between X_i and X_j is between lower average cost versus higher risk. However, if $\pi(\varepsilon)$ can be controlled, then one may seek to choose X_j and $\pi(\varepsilon)$ such that both the average cost and risk are lowered.

Referring to Figure III-1, if we can control $\pi(\varepsilon)$ to have most of its weight within the subset A, then X_1 is a better choice than X_2, from the average performance and the risk point of view. It should be clear that, from the example, the optimal choice of option is dependent on our capability to influence $\pi(\varepsilon)$.

Let us plot $\bar{f}_i$ and σ_i^2, i=1,...,n in a two-dimensional space as in Figure III-2. In the plots with $\pi(\varepsilon)$, X_4 and X_5 are dominated by X_2 and possibly X_1. Therefore, to select the

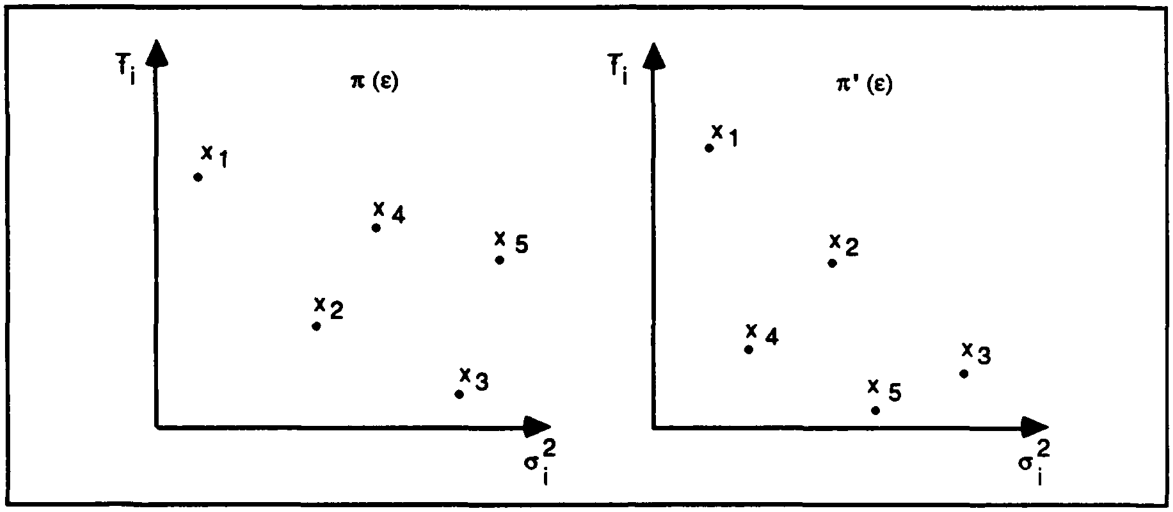


Figure III-2. Plots of $\bar{f}_i$ vs. σ_i^2 as Uncertainty Changes

appropriate options, we need only to consider X_1, X_2, and X_3 and conduct trade-offs between average cost and risk exposure. The plots for $\bar{f}_i$ vs. σ_i^2 will change as the distribution on ε changes. In Figure III-2, we show two plots with different distributions: $\pi(\varepsilon)$ and $\pi'(\varepsilon)$. Note that with $\pi'(\bullet)$, X_4 dominates X_2 and X_3; and the three options subject to trade-off consideration are X_1, X_4, and X_5. From Figure III-2, we would likely conclude that the pair $(X_4, \pi'(\bullet))$ is the best option.

C. APPLICATION TO THE THREE CATEGORIES OF RISK

This section describes how the preceding formulation can be applied to the three categories of risk in product development illustrated at the beginning of this chapter.

1. Uncertainty in Requirements

In the overlapping problem-solving approach, the designer will start designing the product while the requirements for the product are not fully specified. In fact, one of the notions of ULCE is that the designer should participate in helping to determine those requirements.

In this case, ε will represent certain parameters, such as performance, shape, tolerance, and supportability which are subject to uncertainty. Suppose there are three basically different design approaches that can be taken, denoted by X_1, X_2, X_3. The set S_i associated with X_i determines the flexibility that the designer has within the constraints

imposed by that approach. It is assumed that the requirements will be eventually finalized and the corresponding optimum design will be developed within the approach taken.

The curve $f_i(\varepsilon)$ represents an engineering assessment made by the design team of the resulting cost associated with approach X_i if eventually the requirement is ε. The specification team comes up with a distribution $\pi(\varepsilon)$, which is passed on to the design team (feedforward to downstream). The design team takes $\pi(\varepsilon)$ as given and generates a plot like Figure III-2 from which they either recommend an approach to management that has a reasonable trade-off between average cost and relatively low risk or suggest to the requirement specification team that they modify the distribution $\pi(\varepsilon)$ to $\pi'(\varepsilon)$ which will result in lower risk and lower average cost (feedback to upstream).

The negotiation between the requirement specification team and the design team is focused on the interplay between the uncertainty distribution $\pi(\varepsilon)$ and the resulting plots as in Figure III-2. Basically, the suggested distribution $\pi'(\varepsilon)$ will require the requirements specification team to reallocate effort to reduce the most sensitive uncertainty from the design perspective. This may or may not be feasible from the requirements specification team's point of view. However, a plot like Figure III-2 can be used as a catalyst to derive consensus. Figure III-3 illustrates the process described above.

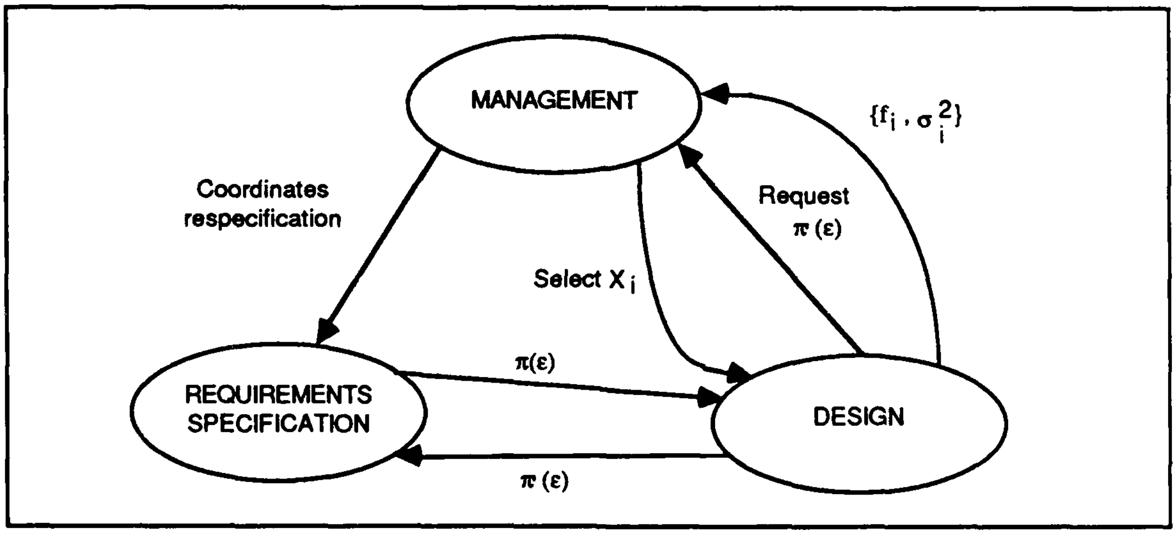


Figure III-3. Handling of Uncertainty in Requirements

2. Uncertainty in Parts Availability

When uncertainty about parts availability exists, the design team must decide whether they should design the product based on standardized parts that are readily available or design the product by specifying the parts needed and ask certain vendors to manufacture those parts. Let X_1 be the approach of using standardized parts and X_2 the other approach. The total life cycle cost of the product consists of design cost, manufacturing cost, operations cost, and support costs. In this case, the uncertainty is the future availability of parts. Let ε be the average lead time for parts when needed. If ε is large, then high support costs will be incurred.

Restricting parts use to standardized parts may incur higher design and manufacturing costs. Assume that under both design approaches we are required to meet the same requirements for reliability and maintainability. Then, assuming that $f_i(\varepsilon)$ is a measure of product life cycle cost, we will have a situation as illustrated in Figure III-4. The slope of both curves will depend on the degree of reliability and maintainability required in the product specification. For $\varepsilon \approx 0$, life cycle cost will be dominated by the design and manufacturing costs, and in this case, the X_1 approach will incur a higher cost. However, as ε becomes large, the total cost will be dominated by the maintenance and support costs. In general, standardized parts imply lower component replacement costs, thus f_2 will overtake f_1 as ε becomes large.

In this case, the distribution on ε depends on the design choice. $\pi_1(\varepsilon)$, the distribution on availability if the parts are standardized, is likely to be concentrated on low values of ε. $\pi_2(\varepsilon)$, the distribution on availability if the parts are not standardized, is likely to be concentrated on high values of ε. Moreover, $\pi_1(\varepsilon)$ is most likely determined by the structure of the standardized vendor's market and thus will be less controllable; whereas $\pi_2(\varepsilon)$ may depend on other elements such as the relationship with the vendor and the specificity of parts required and therefore will be more controllable.

As before, we can compute

$$\bar{f}_i = \int f_i(\varepsilon)\, \pi_i(\varepsilon) d\varepsilon$$

$$\sigma_I^2 = \int (f_i(\varepsilon) - \bar{f}_i)^2\, \pi_i(\varepsilon) d\varepsilon$$

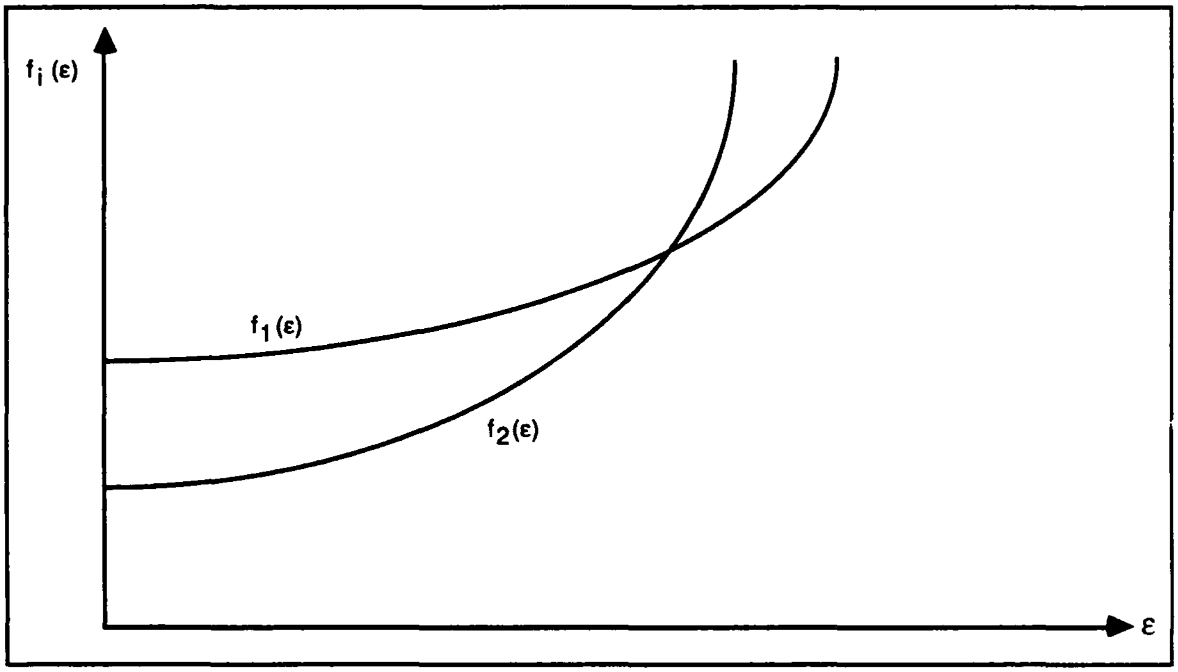


Figure III-4. Total Life Cycle Cost as a Function of Parts Availability

to represent the average cost and risk associated with parts availability. Note that the optimum choice is not clear, since it depends on the following:

- The slopes of the curves $f_1(\varepsilon)$, $f_2(\varepsilon)$ (reliability and maintainability requirements)
- The intercepts of the curves: $f_1^{(o)}$, $f_2^{(o)}$ (design and manufacturing costs)
- The distribution $\pi_1(\bullet)$ (market structure of standardized parts)
- The controllability of $\pi_2(\bullet)$ (capability of influencing vendor's performance).

In general, if there are special features of a component that are unique and absolutely necessary, then standardized parts may not be readily available, in which case X_2 may be the better choice. The analysis indicates that in such cases more emphasis should be devoted to tightening the relationship with the vendor contracted to provide the component. On the other hand, if standardized components can be used, then most likely $\pi_1(\varepsilon)$ will be clustered at a low value of ε, which implies that X_1 is a better choice. For a product that has many component parts, the analysis can be used to determine which component parts should be obtained from standardized markets and which parts from custom or semi-custom markets. Such a determination will provide a guideline for product design. This

case illustrates how downstream uncertainty can influence an upstream decision. This example is discussed in more detail in the next chapter.

3. Uncertainty in New Technology

Suppose that the R&D group is developing a new technology which, if successful and used in the product to be developed, will tremendously reduce the overall product cost. The product can also be developed without the use of such new technology, but the overall product cost will be much higher. However, the product development team does not know the time ε when the R&D group can make the new technology available. The absolute deadline for product introduction is specified as T. Should the product be introduced at an earlier time t, then the company will attain a value $v(t) \geq 0$, for all $t \leq T$ that is monotonic decreasing and $v(T) = 0$. The maximum resources that the product development manager can draw on to complete the project are constrained.

The project manager estimates that if he uses the maximum capacity in developing the product via the conventional approach (does not use the new technology), it will take $T_1<T$ to complete the product development; whereas if he uses the maximum capacity to develop the product and assumes the new technology is available, then he will require $T_2 \in [T_1,T]$ to complete.

The manager has several options. The first option, X_1, is to allocate the full team in developing the product, assuming that the new technology is available. However, at time $t=T-T_1$, if the new technology is still not available, then he must abandon the original development and allocate the full team to the conventional approach to meet the deadline T. We can plot $f_1(\varepsilon)$ as shown in Figure III-5. Here, ε stands for the time that the new technology becomes available. If the new technology is made available before $T-T_1$, then it will be used. We assume in this example that sufficient flexibility is built into the product development process so that the cost of incorporation of new technology is independent of the time when it is made available.

The second option, X_2, is to allocate the full team in developing the product without assuming that the new technology is available; but then, once it is available (before $T-T_2$) switch the full team to the approach of utilizing the new technology. By $T-T_2$, if the new technology is still not available, then it is too late to adopt the new technology. Note that in this case if the new technology is not available before $T-T_2$, the team will continue its original effort and will complete the development at $T_1<T$. The value $v(T_1)$ can be used to

offset the total cost and thus produce the curve $f_2(\varepsilon)$ as in Figure III-5. As compared to X_1, if the new technology is not available by $T-T_2$, the X_2 approach will finish the development later.

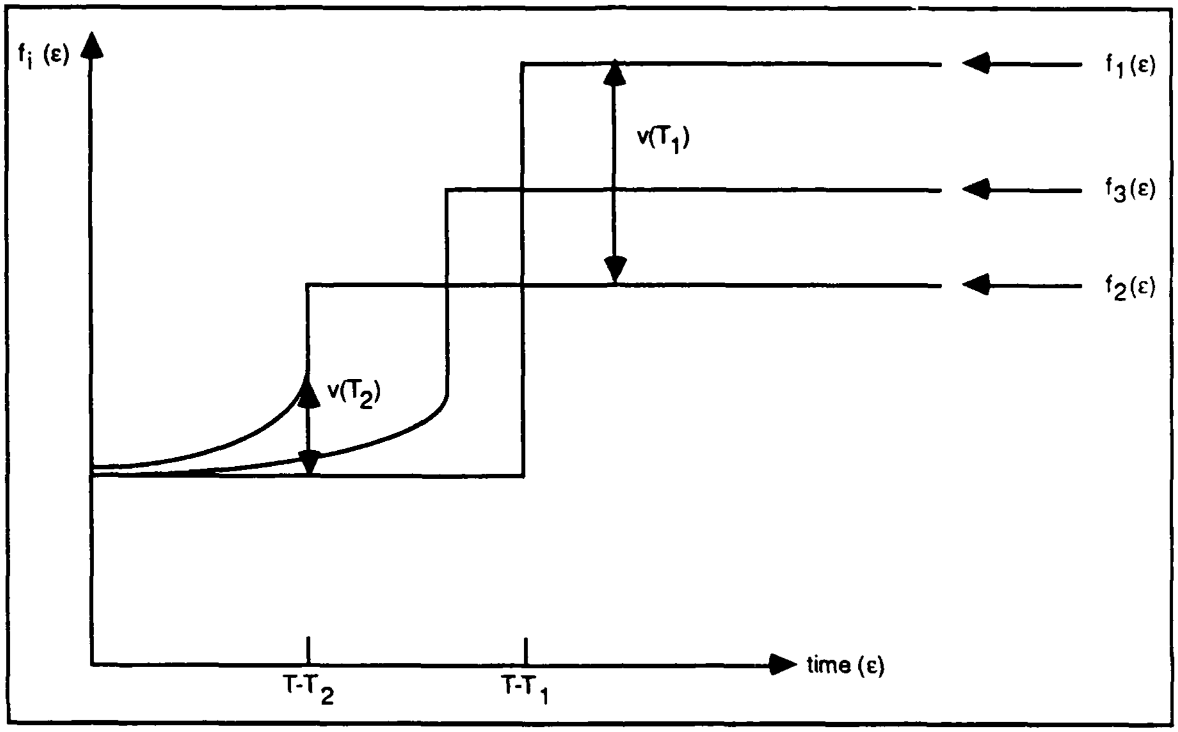


Figure III-5. Cost as a Function of the Time When New Technology is Available

Another option is to split the total resources up into two teams. One team assumes that the new technology is available, and the other team assumes that the new technology is not available. The two teams will merge into one under different events. If the new technology is available early enough so that it can be used and the deadlines still met, then the two teams will merge and proceed using the new technology; otherwise the teams will merge and proceed without the new technology. The maximum waiting time before merging without the availability of new technology is dependent on the relative size of these two original teams. One can view X_1 and X_2 as the two extremes of this option. Conceptually we can have a continuous set of options. For illustrative purposes, we shall only plot one such $f_3(\varepsilon)$ in Figure III-5.

The optimal choice depends on $\pi(\varepsilon)$, the distribution of the time availability of the new technology. If $\pi(\varepsilon)$ is concentrated on lower values of ε, then X_1 is optimal. As $\pi(\varepsilon)$ is shifted to the right, X_3 would be optimal. A further shift of $\pi(\varepsilon)$ to the right will make

X_2 become optimal. This implies that input from the R&D is critical in determining the optimal approach. By having the design team work closely with R&D, we may be able to shift $\pi(\varepsilon)$ to the left, which will increase the chance that the new technology will be adopted and result in a much lower cost. Using the analysis, the manager can determine such an optimal resource allocation.

If the R&D is conducted by another company (supplier), then the analysis can be used to determine the value of having the product team interacting with and even helping the supplier's R&D team to make the new technology available earlier.

The preceding analysis was based on the assumption that $T_2 \in [T_1,T]$. If $T_2<T_1<T$, then instead of Figure III-5, we have Figure III-6. Similar conclusions can be deduced; however, the dependency of optimal option on $\pi(\varepsilon)$ will be different.

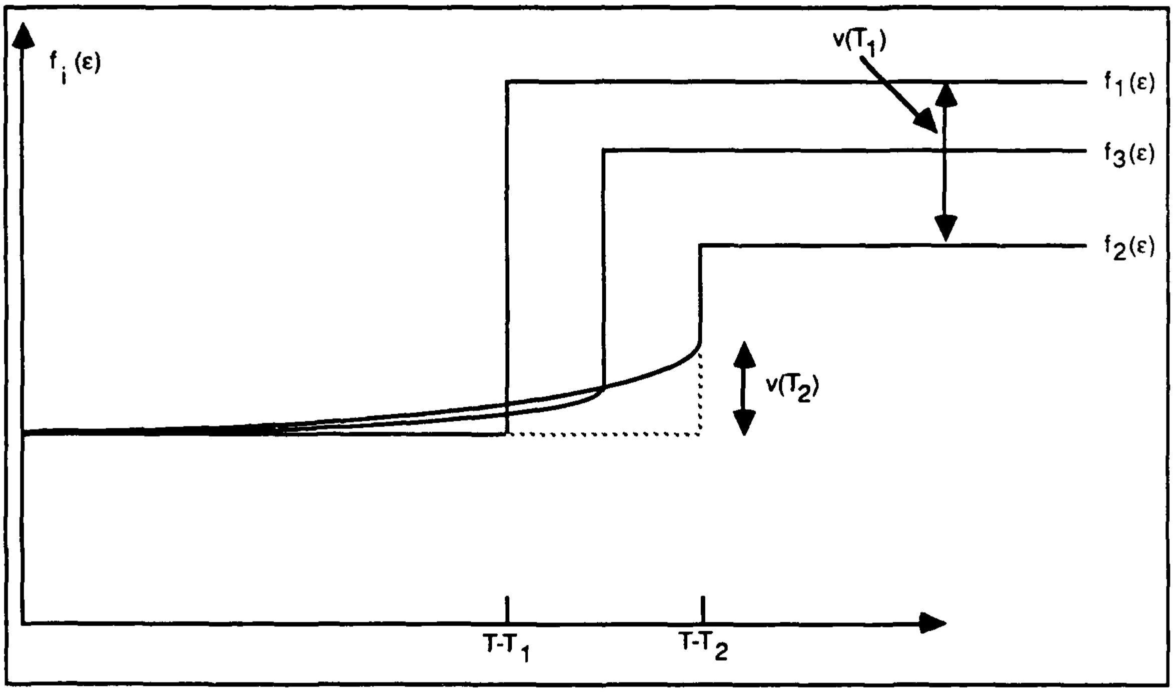


Figure III-6. Variation of Figure III-5 When $T_1 > T_2$

D. GENERAL REMARKS

The basic concept described in the preceding section can be a powerful tool in the management of the product development process. The next chapter describes how the approach can be easily extended to handle multiple overlapping phases. Even though our

discussion focuses on cost as the primary variable of interest, a similar approach can be taken to deal with development lead time.

The approach described in this section is similar in concept to the Taguchi approach for parameter design [Ref. 4]. In Taguchi's approach, a loss function is computed based on the deviations of certain product characteristics from target values in a noisy (random) environment. The objective is to choose a set of design parameters to minimize the expected loss. Our σ^2 is analogous to the Taguchi loss function. In the approach outlined in this chapter, the design parameters are subject to control, and a portion of the random environment may be subject to management control. While the design engineer focuses on selection of design parameters to minimize the loss function, the management focus should be on controlling the environment to allow the engineers to do a better job. Close interaction between engineers and managers is the key to achieving an optimum design.

IV. INTEGRATION OF UPSTREAM AND DOWNSTREAM UNCERTAINTIES

A. THREE-PHASE PROCESSES

In this chapter, we consider a three-phase process in which the activities of the second phase (which for our purposes we assume to be the design phase) are affected by uncertainties in output from the first phase (an upstream phase), and themselves affect uncertainties in the third phase (a downstream phase). This situation is illustrated in Figure IV-1.

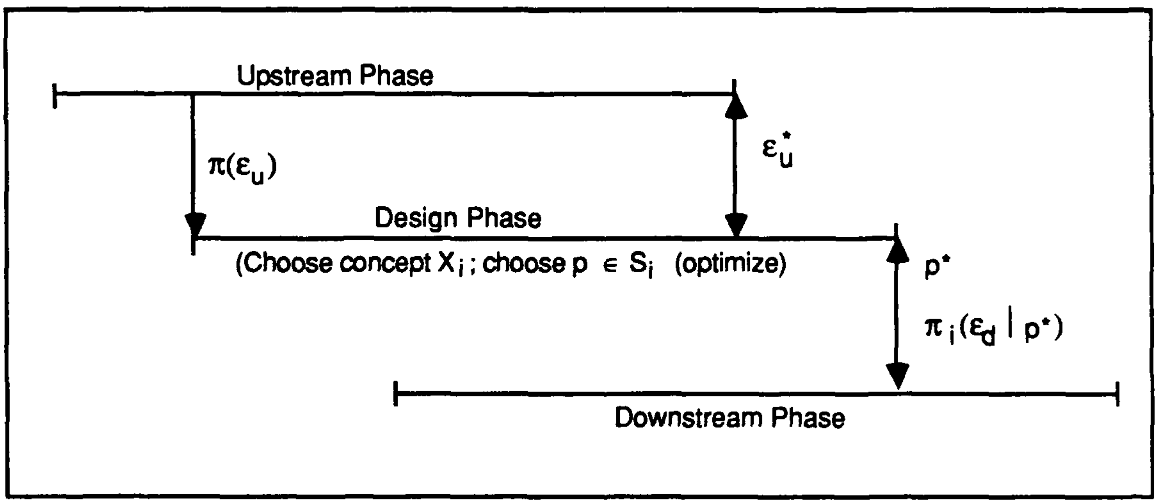


Figure IV-1. Interactions Among Phases in a Development Process

1. Upstream Phase and Design Phase

At the beginning of the design phase, the upstream phase will not have determined its final output, the requirements specification ε_u^*, and will only be able to provide a distribution $\pi(\varepsilon_u)$, which assigns relative likelihoods over several possible requirements specifications. The degree of variability of π is a measure of the uncertainty in requirements that is faced by the design team.

As noted in the preceding chapter, in attempting to design to a particular set of requirements, the designers will choose a design concept X_i, and within this concept (or approach) will seek to identify values for a set of parameters $p \in S_i$, which optimizes the design within the constraints S_i imposed by the concept X_i. Note that we use the term "optimize" in a general way. Strict mathematical optimization is not necessarily implied. In general we assume that optimize means to determine a feasible set of parameters $p \in S_i$ (a "satisficing" solution), which appears to be the best approach possible given the available knowledge and resources of the design team.

Eventually the upstream phase will be concluded, with the final requirements being specified as ε_u^*. We shall refer to the process of proceeding from the distribution $\pi(\varepsilon_u)$ to ε_u^* as the freezing of requirements. After this point, the design team will then proceed to a final design p*. This process is called freezing the design.

2. Downstream Phase

For any $p \in S_i$, uncertainties will also arise due to downstream considerations. We shall denote such uncertainty by ε_d. As examples, ε_d could represent uncertainties in the manufacturing process or uncertainties in the future availability of certain components or parts. The distribution of such uncertainties is influenced by the design approach taken (i) and the choice of parameters $p \in S_i$. We shall denote this distribution by

$$\pi_i(\varepsilon_d \mid p)$$

Note that p is also a function of ε_u, so this can also be represented by

$$\pi_i(\varepsilon_d \mid p(\varepsilon_u)) .$$

In most deterministic design approaches, the final design would be obtained by solving a deterministic optimization [Refs. 11, 12] of general form:

$$\min f(p, \varepsilon_u^*)$$

$$\text{s.t. } g(p, \varepsilon_u^*) \leq 0$$

This approach ignores the downstream uncertainties that will be influenced by the choice of $p(\varepsilon_u^*)$.

At the beginning of the downstream phase, the downstream team will face uncertainties in the output from the design phase. After the design is frozen at p*, however, the downstream team may then optimize its activities for the design p*. When the downstream phase is the production phase, this amounts to optimizing the production

process for a given design. At this point, techniques for continuous production process improvement become operational. These activities serve to change the form of $\pi_i(\varepsilon_d \mid p(\varepsilon_u^*))$.

3. Integration of Phases

As in the two-phase processes discussed in Chapter II, the key issue in handling both upstream and downstream uncertainties involves proper management of the reduction in these uncertainties over time. In the early part of the design phase, the design team interacts only with the upstream requirements team. In the middle, the design team will interact with both upstream and downstream teams. After the upstream input is frozen, the design team will interact mainly with the downstream team. In the latter portion, if the downstream phase is the production phase, the design activity will include optimization of the design for production. Production, on the other hand, will seek to optimize production processes given the design. Since both the design and production processes are uncertain at first, continual interaction between teams must occur to reduce this uncertainty and allow convergence to an overall solution. This process, in the case of design and production, is known as simultaneous engineering.

Simultaneous engineering involves reducing downstream uncertainties over time. However, it should be noted that, unlike the upstream case, all downstream uncertainties will not be totally resolved. Until the product life cycle is complete, some downstream uncertainties will remain.

To manage the process of reduction of uncertainty, we need to develop a strategy. To develop such a strategy, we shall begin by considering the design phase and its problem of developing an optimal design in the face of upstream and downstream uncertainties. To do this, we need to develop a metric to measure what we mean by optimality.

B. PARAMETER OPTIMIZATION

In this section we will develop an approach to optimizing designs in the face of downstream uncertainties, and in the next section we address management issues of a development process based on this approach.

1. General Product Development System Model

Figure IV-2 depicts a conceptual model of the product development process, which highlights the features of that process of interest to us.

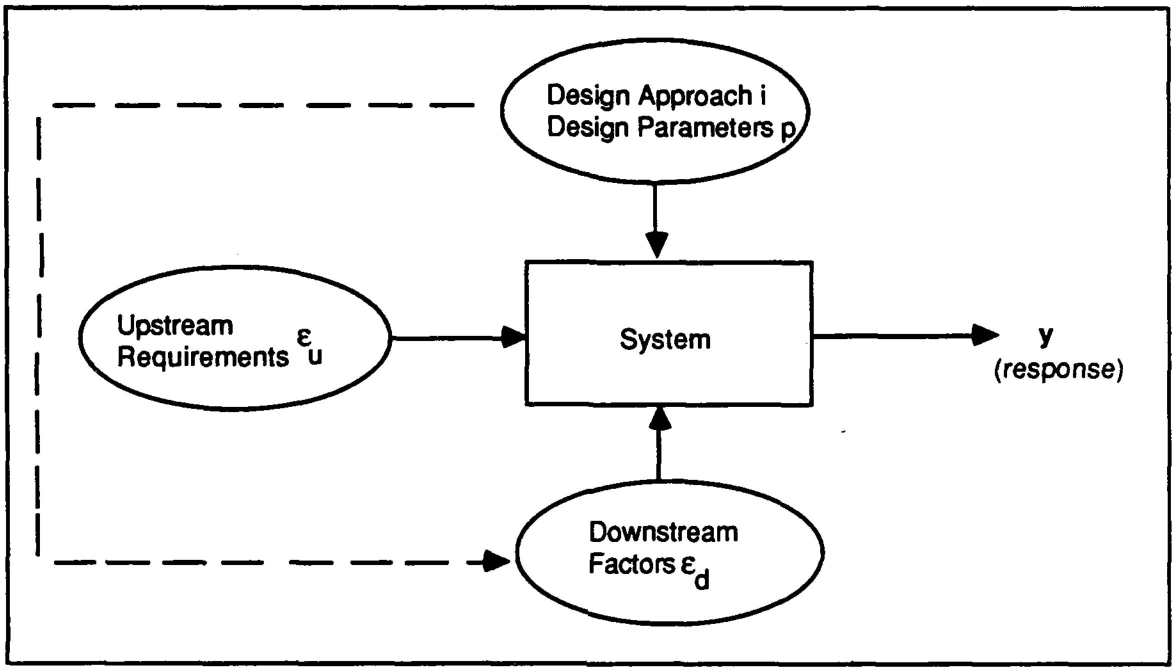


Figure IV-2. Development Process System Model

In this model, the system produces a response y, which is a random vector of outputs driven by the design (concept selection and choice of design parameters) input requirement specifications that are subject to uncertainty for some period of time, and downstream factors that are also subject to uncertainties that are conditional on the design approach and parameters chosen. Our objective is to control the inputs and choices in the model in such a way to produce outputs that are good in some sense. Our options include

- Managing the uncertainty in ε_u (controlling the formal process for determining the product requirements).
- Managing the downstream uncertainty to the extent possible.
- Selecting a design concept i with an appropriate balance of expected performance and risk.
- Choosing the design parameters once the concept has been selected.

We briefly discussed the first three of these options in the last chapter, and they are addressed again in more depth later in this chapter. In this section, we will concentrate on

accomplishing the last point in the face of downstream uncertainty, assuming the concept i and the requirements specification ε_u are fixed.

2. Response Function

While there are many possible ways to measure the response of the system, we propose that the vector y should consist of three major components:

- a vector y_T of physically measurable target performance characteristics of the product being developed
- y_c, the product life cycle cost
- y_l, the lead time for delivery of the first product.

Thus $y = (y_T, y_c, y_l)$ in our formulation.

The vector y_T would consist of product attributes such as weight, range, and maximum speed for a product such as an aircraft. For other types of products, other measures would be appropriate. The important thing is that we must be able to physically measure y_T for each product as it is placed in service.

In contrast, y_c cannot be physically measured at the time of introduction, since it depends on events that have not yet occurred, such as field usage factors and costs and availability of manpower and spare parts. In principle, we can infer the effects of changes in p on y_T through experimentation, but this is not possible with y_c. The best we can do is to predict y_c, and in the design phase, such predictions will be very uncertain at best. While the absolute values of y_T have meaning, predictions of y_c will be useful only in a relative sense--to compare and rank designs whose other characteristics are equivalent.

Lead time also differs from y_T. Lead time may be predicted during the design phase, but with considerable uncertainty. At the time of product introduction, lead time is known, but by then it is too late to change it. As with y_c, y_l is a factor useful in ranking and comparing designs, and we should generally seek designs with the lowest value possible. Product introduction time considerations often determine limits for lead time. Using lead time as a constraint rather than as part of our objective in the design process may be more appropriate.

In the development process we should usually seek to minimize y_c and minimize y_l, or at least constrain it. In the case of y_T, however, we usually will have explicit goals

or target values provided. These values, which we denote by $\bar{y}_T(\varepsilon_u)$, are clearly related to the requirements and also to the design concept. The process of generating $\bar{y}_T$ from ε_u is a key part of the systems engineering process. While we assume that this process is given here, the development of better methodologies in this area is an area of research that deserves more attention.

In summary, we may recast the design parameter optimization problem as:

Seek to attain, as best as possible, the physical performance goals, while minimizing life cycle cost and not exceeding lead time constraints.

Note that in contrast to $\bar{y}_T$, which is derived from the specification, y_T is a function of the design concept and parameters, ε_u, and ε_d. Thus, y_T is a random quantity. The degree to which we attain product goals will vary from product to product--some will turn out well and others will not. This randomness must be considered in solving the problem.

3. Mathematical Formulation of Parameter Optimization Problem

The problem stated above may be mathematically formulated in a variety of ways. One approach would be to formulate the problem using the goal programming approach (for example, see Mistree, et al. [Ref. 3]). In this paper, following the approach taken by Taguchi [Ref. 4], we will compute a measure of failure to attain the goal $\bar{y}_T$ based on a quadratic function of the absolute deviation of the actual performance characteristics from the target vaules. This measure is thus defined as

$$L_{i,p}(\varepsilon_u, \varepsilon_d) = \| y_T - \bar{y}_T \|^2 = \sum_i (y_T(i) - \bar{y}_T(i))^2$$

$L_{i,p}$ measures the sum of the squared derivations of physical product performance characteristics from the target goals. The Taguchi method [Refs. 4, 5, 6, 7] of parameter optimization seeks to minimize the expected loss function in the presence of external noise. In our formulation, this translates into:

$$\min_{p \in S_i} E_d[L_{i,p}(\varepsilon_u, \varepsilon_d)] \qquad (1)$$

where $E_d(f) = \int_\Omega f(\varepsilon_d)\pi_i(\varepsilon_d \mid p(\varepsilon_u))d\varepsilon_d$.

An alternate expression for the minimization (1) is given by

$$\min_{p \in S_i} \left[\| E_d y_T - \bar{y}_T \|^2 + \mathrm{Var}_d (y_T) \right] \tag{2}$$

where $\mathrm{Var}_d(f) = \int_\Omega (f(\varepsilon_d) - E_d(f))^2 \pi_i(\varepsilon_d) d\varepsilon_d$.

The minimum value for (1) or (2) is denoted by $\sigma_i^2(\varepsilon_u)$. $\sigma_i^2(\varepsilon_u)$ is considered a measure of the optimum level of quality attainable with design concept i in the presence of downstream uncertainties π_i. It can also be considered as a measure of the downstream risk of not meeting the performance requirements.

Three things should be noted about this approach. First, the upstream requirements specification ε_u is treated as fixed. Second, the downstream uncertainty distribution is fixed. Exogenous changes to π_i are not considered here. Finally, the method is focused exclusively on physically measurable performance characteristics. Life cycle cost and lead time are not considered. Thus the minimization problem stated in (1) and (2) addresses only the first part of the design parameter optimization problem.

To extend this method, let us first consider the addition of life cycle cost to the problem. Since, from the previous discussion, life cycle cost should be minimized while attaining good quality, we propose the following formulation. Consider the following problem.

$$\min_{p \in S_i} E_d(y_c) \tag{3}$$

$$\text{s.t. } E_d(L_{i,p}(\varepsilon_u, \varepsilon_d)) \le \delta, \ \delta \ge \sigma_i^2(\varepsilon_u)$$

Note that $\delta \ge \sigma_i^2(\varepsilon_u)$ guarantees a solution, while for $\delta < \sigma_i^2(\varepsilon_u)$ there is no solution. For $\delta \ge \sigma_i^2(\varepsilon_u)$, let $y_c^*(\varepsilon_u, \delta)$ denote the minimum obtained in this problem. Then it is clear that for $\delta_1 \ge \delta_2 \ge \sigma_i^2(\varepsilon_u)$, we have

$$y_c^*(\varepsilon_u, \delta_2) \ge y_c^*(\varepsilon_u, \delta_1).$$

Thus, the relationship between y_c^* and δ is as shown in Figure IV-3.

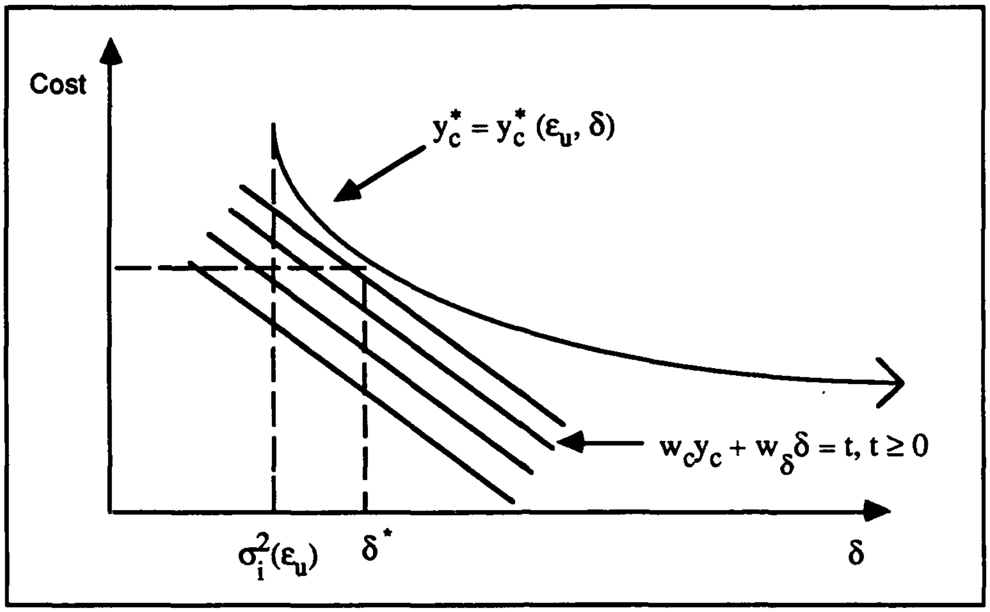


Figure IV-3. Dependence of Minimum Life Cycle Cost on Allowable Quality

If we consider the loss function $\sigma_i^2(\varepsilon_u)$ as a measure of quality, we see that the curve in Figure IV-3 shows the trade-off between life cycle cost and allowable quality (measured by δ). While the simple optimization in (2) by itself optimizes quality, the cost of attaining this optimum may be very high. If we can quantify our relative desires for quality and low cost by weights w_c and w_δ, then we can compute a dissatisfaction function:

$$J_i(y_c, \delta) = w_c y_c + w_\delta \delta \qquad \text{(i = design concept)}$$

Then various levels of dissatisfaction correspond to the family of lines shown in Figure IV-3. The optimum level of dissatisfaction is achieved at the point of tangency of this family of lines to the (y_c^*, δ) trade-off curve. This is found by solving the equation

$$\frac{\partial y_c^*}{\partial \delta} = -\frac{w_\delta}{w_c} = \lambda$$

Let the solution be denoted δ^*. Then λ measures the price we pay, in terms of increased dissatisfaction, for a unit change in quality near the optimum. The corresponding cost and dissatisfaction levels at the optimum are

$$y_c^*(\varepsilon_u, \delta^*)$$

$$J^*(y_c^*(\varepsilon_u, \delta^*), \delta^*) = w_c y_c^*(\varepsilon_u, \delta^*) + w_\delta \delta^*$$

Since δ^* is computed by an optimization, we can suppress the dependency and denote the latter quantity by

$$J_i^*(\varepsilon_u)$$

If we wish to incorporate lead time as well as cost, this can be done as follows:

Consider the problem:

$$\min_{p \in S_i} \left[\gamma_1 E_d(y_c) + \gamma_2 E_d(y_\iota)\right], \ \gamma_1, \gamma_2 \geq 0 \ , \ \gamma_1 + \gamma_2 = 1$$

$$\text{s.t. } E_d(L_{i}(\varepsilon_u, \varepsilon_d)) \leq \delta \geq \sigma_i^2(\varepsilon_u) \tag{3'}$$

An analogous development to the one given above for cost and quality will lead to a new dissatisfaction function $J_i^*(\varepsilon_u) = w_c y_c^* + w_\delta \delta^* + w_\iota \iota^*$.

We shall refer to the function $J_i^*(\varepsilon_u)$ as the generalized loss function, since it incorporates not only losses due to poor quality, but also due to high cost and excessive time to market in developing the product.

As we shall see in section C of this chapter, $J_i^*(\varepsilon_u)$ can be used in place of the general cost:

$$f_i(\varepsilon_u) = \min_{p \in S_i} C_i(\varepsilon_u, p)$$

that was introduced in the previous chapter to handle upstream requirements uncertainty. Thus, we may now apply the approach of that chapter to handle both upstream and downstream uncertainties in an integrated manner.

4. Computational Issues

Computation of $J_i^*(\varepsilon_u)$ involves solving the optimization problems (1) and (3), which requires a model for the response **y** as a function of the parameters p and the downstream uncertainty ε_d. Moreover, a model for the downstream uncertainty distribution is also needed. Such a model can either be obtained from scientific or experimental knowledge. If the dependency of **y** and π_d on these factors can be specified in closed mathematical form, analytical optimization methods can be applied in solving (1) and (3). If, however, the relationships can only be represented in some symbolic form or derived through simulation, then problems (1) and (3) must be solved using some sort of search

approach. In most practical cases, one needs to incorporate specific domain knowledge or some structural knowledge about the problem to devise an efficient search method to solve (1) and (3). This is where artificial intelligence (AI) technology, in particular knowledge-based technology, may be extremely useful.

5. Developing the Quality Versus LCC Trade-Off Curve

Conceptually, computing the trade-off curve in Figure IV-3 is straightforward, but practically, it may be a difficult or even analytically intractable problem. Even so, the mathematical formulation provided by the equations given in the preceding section can serve as a guideline in developing a practical solution method that approximates the mathematical formulation. One approach to this is as follows:

Let p_0 be our choice of design parameters after solving optimization problem (1). Problem (1) could be solved using a variety of methods, from standard mathematical optimization techniques to experimental design methods, such as those recommended by Taguchi or others. Now let us develop an estimated LCC using design p_0 as a baseline. This has been done in many real development efforts [Refs. 8, 9], and standard templates (models) exist for such calculations. Next let us identify all of the exogenous random variables in the LCC model that depend on p_0 or on specific management choices (how to manage the maintenance process, for example). Next we vary the design parameters from p_0 and examine the effect of these variations on LCC via the LCC model. With certain assumptions on the behavior of the exogenous variables, the effects of these variations on LCC may be estimated. If we then find the direction of change that gives the greatest change in LCC, we have identified where we have optimum leverage on LCC through design parameter variation. We next examine the effect of such a change on quality level. By alternating between considerations of quality and LCC, we hope to arrive at a new choice of design parameters that gives us better LCC at minimal reduction in quality. The search procedure described above can be implemented as a local search method in seeking δ^*, the level of quality at which our dissatisfaction $J_i^*(\varepsilon_u)$ is minimized.

C. MANAGEMENT OF UNCERTAINTIES

1. Management of Upstream Requirements Uncertainties

In the preceding discussions, the requirements specification ε_u has been regarded as given. Clearly, we can also regard it as a control parameter in design, as done by Taguchi [Refs. 4, 5, 6]; however, there is a subtle difference between ε_u and p: the choice of p is made after ε_u--p represents design parameters chosen by the designer after ε_u is specified. ε_u, in contrast, is chosen after realizing what can be achieved in fulfilling certain needs in a cost-effective manner.

Let Ω represent the range of ε_u that the upstream members consider as feasible requirements that can be achieved in fulfilling certain needs. The different degrees of likelihood that a particular ε_u will become the final requirements specification is represented by $\pi(\varepsilon_u)$ defined on Ω. $\pi(\varepsilon_u)$ is normalized to give

$$\int_{\Omega} \pi(\varepsilon_u)\, d\varepsilon_u = 1 \tag{4}$$

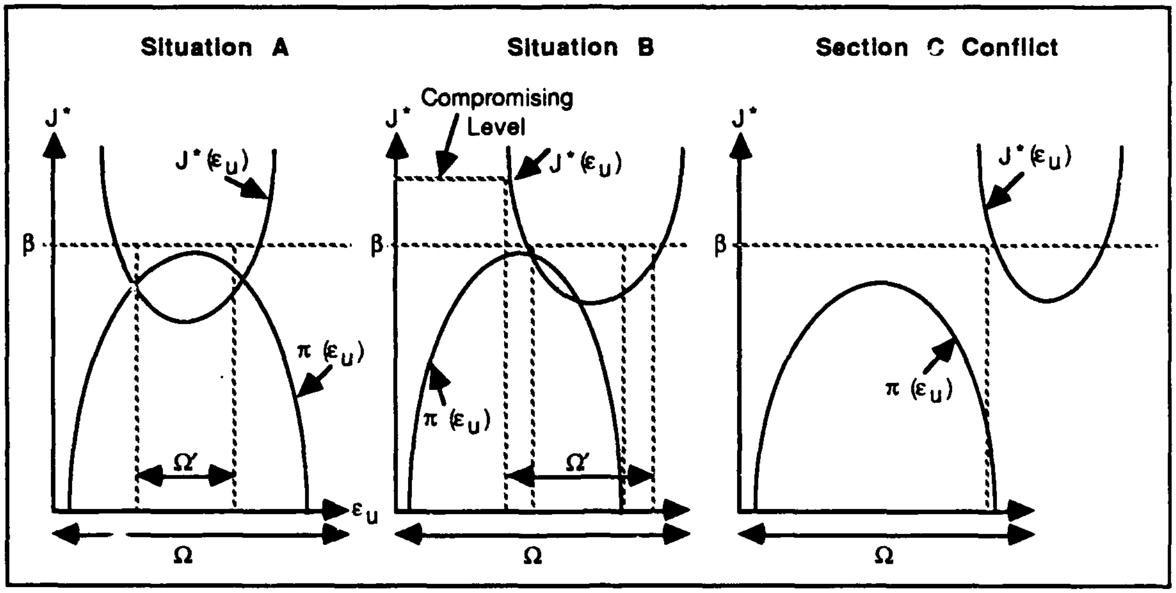
If Ω is a discrete set, then (4) is replaced by

$$\sum_{\varepsilon_u^{(j)} \in \Omega} \pi(\varepsilon_u^{(j)}) = 1 \tag{4$'$}$$

Note that $\pi(\varepsilon_u)$ does not represent an objective probability distribution for ε_u, but rather represents our initial assessment of how likely the requirements will be finally frozen to ε_u.

If $\varepsilon_u^o \in \Omega$ is such that total dissatisfaction level $J^*(\varepsilon_u^o)$ is large, then while ε_u^o is a feasible set of requirements that can be achieved in fulfilling certain needs, the performance and/or cost of a product designed using such these requirements as guidelines will be unsatisfactory. Let Ω' be a subset of Ω constructed by eliminating all ε_u^o that yield unsatisfactory performance or cost.

Now there are three types of situations that may arise, as illustrated in Figure IV-4. In Situation A, we have the good fortune in that what we anticipate to be the most probable requirements specification leads to a final design with acceptable dissatisfaction level. In situation B, there is some compromise between requirements and dissatisfaction. Situation C occurs when there is conflict between upstream requirements and downstream performance or cost achievement. In situations A and B, the new range of possibilities for ε_u can be reduced to Ω'; and the new $\pi'(\varepsilon_u)$ can be modified by adjusting $\pi(\varepsilon_u)$ to fall



β = threshold value for unsatisfactory performance.

Figure IV-4. Upstream-Downstream Interactions

within the range Ω'--simple adjustment guidelines could be that if $\sigma_0^2(\varepsilon_u)$ and $y_c^*(\varepsilon_u)$ are low, then adjust $\pi(\varepsilon_u)$ upward and vice versa. The newly adjusted $\pi'(\varepsilon_u)$ is then normalized within the range Ω'. A possible change from $\pi(\varepsilon_u)$ to $\pi'(\varepsilon_u)$ is illustrated in Figure IV-5. Management judgment is necessary in requiring such a modification, which can be different in different situations.

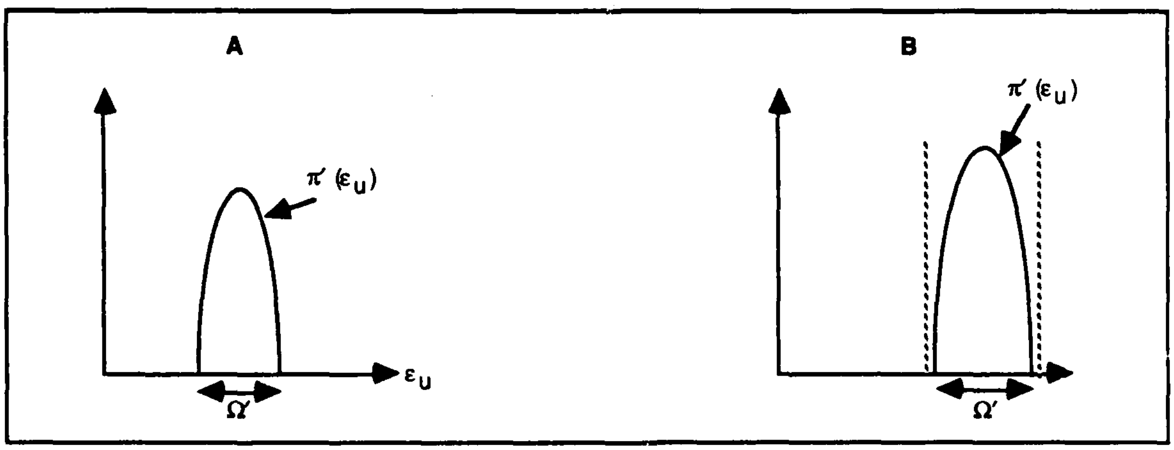


Figure IV-5. Modifications in $\pi'(\varepsilon_u)$ for Unconflicting Situations

The case of conflict indicates the situation in which all feasible requirements specifications $\varepsilon_u \in \Omega$ will lead to unsatisfactory product performance and/or cost. An

effort to resolve the conflict as early as possible is crucial. Otherwise, the continuation of the development process will lead to an extremely unfavorable outcome that will be very expensive to fix. The upstream requirements team needs to reexamine the rationale they used in arriving at Ω and $\pi(\varepsilon_u)$. The design team can point to specific requirements that lead to the unfavorable outcome or explore whether certain downstream uncertainties can be reduced. The process of conflict resolution will vary for different situations. However, identifying the need for such a process to take place in the early product development process will lead to improvements in total product development lead time.

2. Selection of Design Concept

In this section we consider how to select from alternative design concepts, assuming the initial requirements uncertainty is represented by $\pi(\varepsilon_u)$ as in Figure IV-6. As an example, suppose that three different basic approaches are proposed by three different designer groups. Each group has gone through the generalized loss function computation of Section D.1 and three different curves $J_i^*(\varepsilon_u)$ have been obtained as illustrated in Figure IV-6. Approach 1 will always result in a satisfactory outcome. If such an approach is adopted, then we can just let the uncertainty in ε_u be reduced naturally. If, however, the second or third approach is to be taken, the requirements team must determine whether those ε_u that provide lower $J_i^*(\varepsilon_u)$ (i = 2 or 3) can actually fulfill the needs. In fact, Figure IV-6 provides a focus on the range of ε_u that the requirements team needs to explore. The fact that the third approach can lead to substantially improved satisfaction within certain ranges of ε_u stimulates the requirements team to reexamine its original assumption in terminating $\pi(\varepsilon_u)$ at lower values. A new assessment may indicate that the requirements specification can be reduced to the region surrounding the minimum of $J_3^*(\varepsilon_u)$, leading to selection of approach 3 as best.

If the requirements team feels that $\pi(\varepsilon_u)$ can be shifted somewhat to the right, then approach 1 should probably be eliminated from consideration, because the specification can probably now be restricted to Ω' (with $\pi(\varepsilon_u)$ modified appropriately), and with such a restriction approach 2 now gives a lower dissatisfaction level than approach 1.

3. Dynamic Reduction of Requirements Uncertainties

Suppose that a specific design approach i is chosen. The management of the overlapping product development process must then determine how to control the shape of

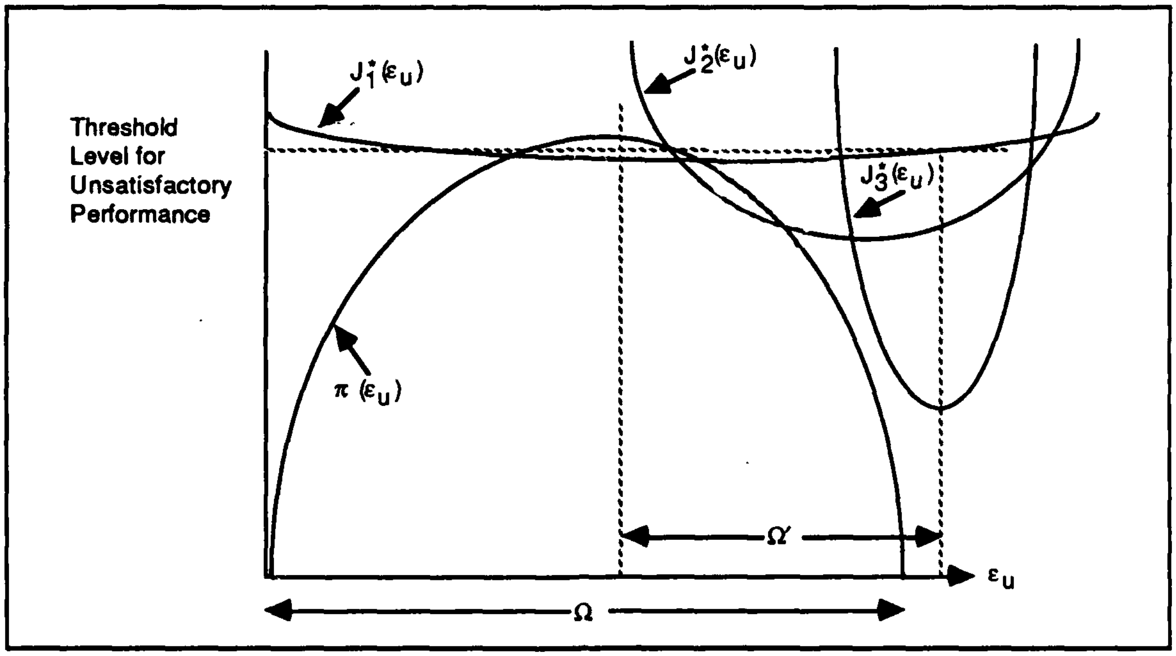


Figure IV-6. Comparison of Three Basic Design Approaches

the funnel--managing the dynamic reduction in requirements specification uncertainties over time. In Sections C.1 and C.2, we described how the original uncertainty $[\Omega, \pi(\varepsilon_u)]$ is refined to $[\Omega', \pi'(\varepsilon_u)]$ after going through a full cycle in integrating downstream and upstream analysis in a nonconflicting situation. $[\Omega, \pi(\varepsilon_u)]$ can be further refined if we can

- Obtain better knowledge of what is achievable in fulfilling needs--expend resources in understanding what are the real needs and what is achievable via technology.
- Compute $J^*(\varepsilon_u)$ more accurately. In the preliminary evaluation of downstream uncertainties, for example, a simple model may have been used in order to get a quick first-cut analysis. Thus, modeling error may be responsible for undesirable dissatisfaction measurements in part of Ω. One may thus expend resources to refine certain components of the model that will reduce the downstream uncertainties. Other ways to reduce downstream uncertainties include modification of the design approach (such as reducing the number of components or using standardized parts). These activities may lead to a more accurate characterization of J^* over the region Ω, giving us a better picture of how to move to an Ω' with much lower dissatisfaction levels.

Determining what activities should be carried out dynamically over time to reduce requirements uncertainties as quickly as possible is the key management control issue.

Some uncertainty reductions occur passively as the result of certain exogenous events; others are planned by management control. This control process can be better represented by a heuristic rather than an analytical process, although some analysis may be useful in supporting the heuristic process.

4. Flexible Design

In the beginning of the design phase in an overlapping process, the design team must be designing when the requirements are not completely specified. Even though a basic approach may have been selected, the team will want to build flexibility into the early design decisions so that when the requirements are refined later, the design space will not have been so constrained by the early decisions as to prevent the team from achieving the final specification. One way to do this is as follows:

Consider a certain design approach i. Let j=1,...n and

$S_{i_j} \subset S_{i_{j+1}}$, j=1,...n be subsets of the parameter space S_i.

Thus, within the approach i, we can have a subapproach (i_j) which is characterized by additional constraints that are placed in the parameter space S_i. The restriction $S_{i_j} \subset S_{i_{j+1}}$ implies that the approach (i_j) is less flexible than approach (i_{j+1}) within the basic approach i. In general, increased flexibility will mean higher design cost. Clearly, $\sigma^2_{i_j}(\varepsilon_u) \geq \sigma^2_{i_{j+1}}(\varepsilon_u)$: more flexibility will also result in higher quality. The effect of flexibility on LCC is not clear. While less constraints allow more freedom in finally choosing a design with a low LCC, the cost for flexibility may be substantial. Therefore, a compromise is needed to determine the optimum flexible design approach.

We can add a step increase in flexibility by having parallel design teams take more than one basic approach and within each basic approach determine the optimum flexibility level. Although this method will increase the design cost in some highly uncertain situations, parallel design teams may be the best approach.

The determination of the optimum level of flexibility depends on the uncertainty levels. Thus as the requirement uncertainties are reduced over time, the optimum flexibility level will also be reduced. As the requirements are fully specified, the flexibility level will be reduced to zero: $S_{i_j} \rightarrow p(\varepsilon_u^*)$. The dynamic aspect of how the optimum flexibility level

will be determined is not worked out completely here, but we believe it can be developed by further extending the reasonings as put forth in Sections C.1-C.3.

5. Staging of Development Phases in Product Development

In the discussions in Sections C.1-C.4, we have assumed that the design phase has one upstream phase (requirements specification) and one downstream phase. In practical situations, more than one phase upstream or downstream may exist. This section discusses the case where two upstream phases precede design. In the planning of an overall product development process, the important issues to be considered are the identification and ordering of the phases involved. In an overlapping process, phase 1 precedes phase 2 if the output of phase 1 is frozen before that of phase 2.

The design team requires two different types of specification. The first type is related to the physical requirements that the product is supposed to have; and the second type is related to new technology that is supposed to be incorporated in the product. If new technology is to be incorporated into the product, should we freeze the technology features or the physical requirements first? The following sections describe two different orderings, which are appropriate under different situations.

a. Need-Driven Process

Consider the case where we desire to integrate a set of new technologies in a product development. These new technologies are proven and their features are known, but they have never been integrated before into any product similar to the one we are developing. Therefore, how they should be integrated and what the resulting product capabilities would be are still unknown. Since the basic features of these technologies are known, we may be able to bound the realm of capabilities after they are appropriately integrated. Since there are numerous ways to integrate these technologies, the technology integration process can be facilitated by specifying the physical requirements first, which will provide a focus for integration. Therefore, in this situation, we should freeze the physical requirements before freezing the technology integration.

Note that in this case, the physical requirements that the product should meet are the driving force. These requirements reflect our needs for the product. We refer to this situation as a need-driven or market-driven process.

b. Technology-Driven Process

While the design team is designing a product, an R&D team may be developing a new technology that can significantly improve certain attributes of the product. For competitive reasons (either in a defense or commercial sense), we may desire to incorporate such technological developments into the product design as early as possible. While the R&D team may assure management that the new technology will be available in time for incorporation into the new product, such an estimate is usually not accurate and in many cases is optimistic. Moreover, the precise features that can be successfully achieved with new technology may not be known, although some range of estimates for these features can be provided by the R&D team.

In this case, no meaningful physical requirements can be frozen prior to availability of the new technology, since they will depend on whether such a superior technology can be made available, which will affect our desires for the physical requirements of the product. We argue that, in this case, the technology features should be frozen before the product's physical requirements.

We refer to this as a technology-driven process since the successful development of the new technology provides a focus for specifying the physical requirements which, in turn, drives the product development process.

Note that both processes incorporate technology development and marketing (relating needs to physical requirements specification) in the product development process. The distinction is which activity provides the focus that drives the product development. The technology-driven process is more risky than the market-driven process; however, the technology-driven process plays a key role in fostering worldwide competitiveness and is responsible for most innovative products developed in this world. For complex products, we may actually use a mix of needs-driven and technology-driven processes--certain new technologies will be well tested and used for the first time in the product application, while others may still be pending completion by R&D groups. In this more complex situation, the appropriate staging becomes even more important to control the success of product development. We will generally have an interlacing of partial technology and requirement freezing during the whole specification process (see Figures IV-7 through IV-10).

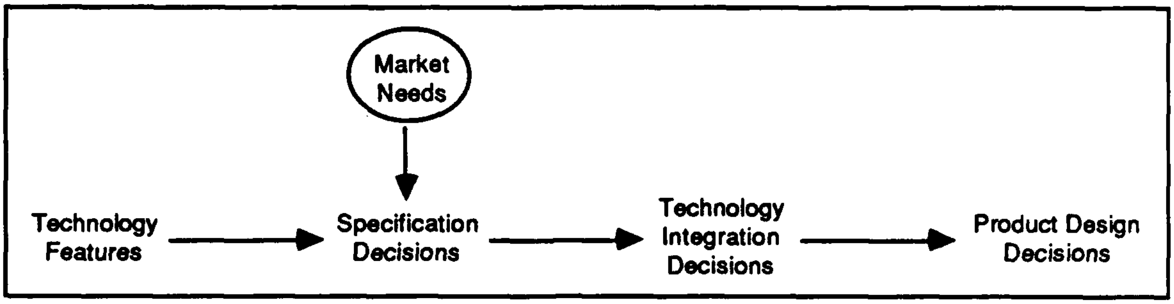


Figure IV-7. Market-Driven Process

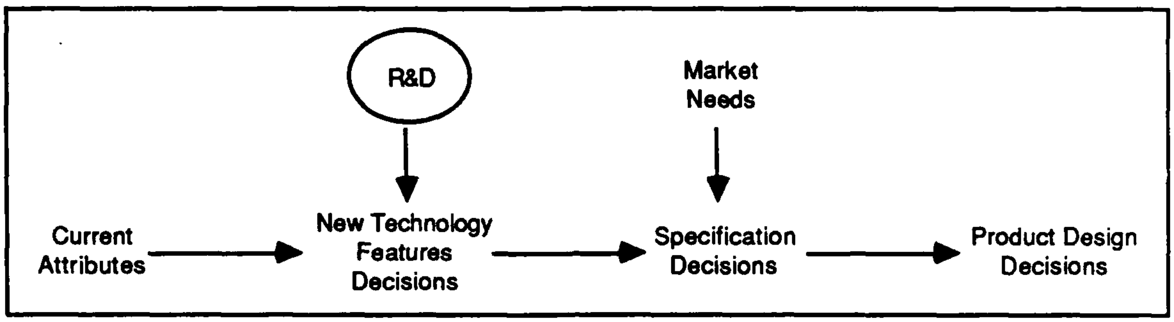


Figure IV-8. Technology-Driven Process

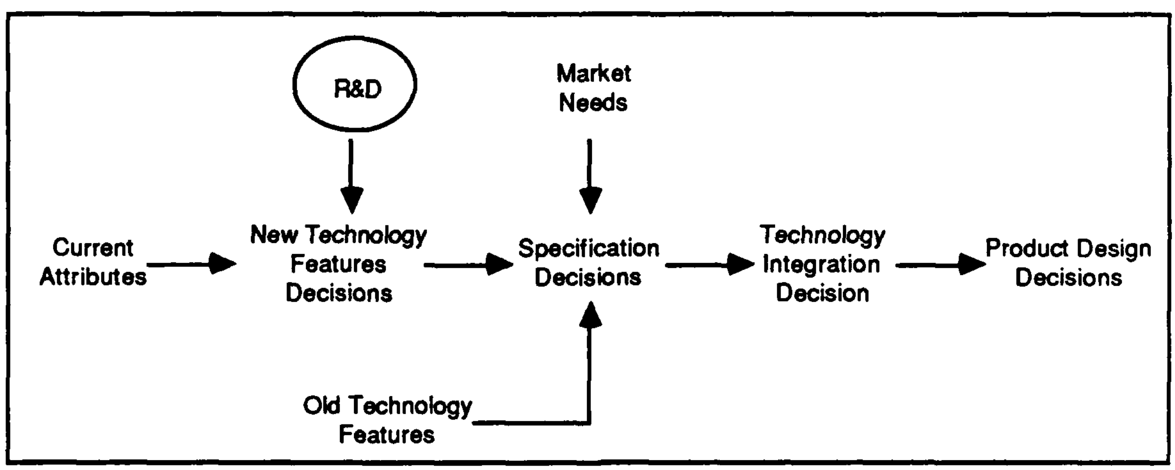


Figure IV-9. Mixed Process

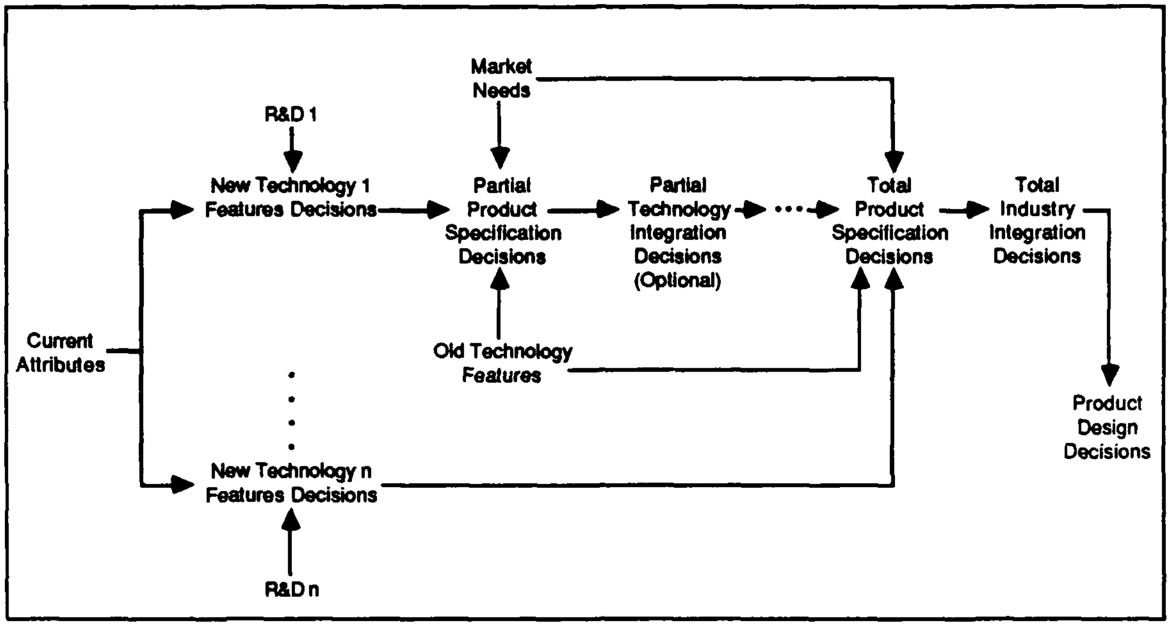


Figure IV-10. Complex Mixed Process

D. APPLICATIONS TO MANAGING UPSTREAM UNCERTAINTY

1. Concurrent Engineering

Recent initiatives, such as the Defense Advanced Research Projects Agency (DARPA) Initiative in Concurrent Engineering (DICE), have advocated the conversion of a sequential product development process into one in which the technology development, design, and manufacturing engineering activities are pursued concurrently. The focus has been on developing a parallel information/computing architecture that allows synchronized evolution of these activities with progressive refinement [Ref. 10]. However, what has not been addressed is the issue that the conversion of sequential activities into parallel activities creates uncertainties that must be managed properly to ensure success. This section addresses such issues. We believe these issues are fundamental to any concurrent engineering effort.

Two issues of major importance in concurrent engineering are staging phases and freezing of phase decisions through dynamic reduction of ambiguity through integration of upstream and downstream analyses. When technology development is in its infancy, any concurrent effort in design is probably too costly. Therefore, the issue is at what stage of

technology development should the design effort start. The marketing activity that focuses on discovering people's needs must also occur at the same time.

Once a staging decision is made, the inherent overlapping paradigm introduces upstream and downstream uncertainties as discussed in Section C, and a methodology is needed to address this problem.

We believe that the discussions in Sections B-C can provide a proper top-level framework for the development of an appropriate information management system that can support concurrent engineering. Of course, a great deal of research is needed to enable such a development to be successful.

2. Planning of a Science and Technology Program in Conjunction with Advanced System Developments

S&T research is an independent activity with the primary objective of advancing the frontier of knowledge, which will lead to innovative technological development. Such advancements will not only affect specific vertical applications but also provide a platform for many advanced product developments. For example, basic research in advanced materials will affect the aerospace, automobile, and many other industries.

The basic premise of concurrent engineering is to integrate such research activity into a specific advanced product development process. The research is treated as an earlier phase in the product development process. By performing one cycle of downstream and upstream analysis, one can determine whether the status of basic research can potentially provide the technology to ensure the success of the perceived advanced product (no conflicts arise). If no conflicts arise, then one can apply the analysis discussed in the preceding paragraphs to evaluate the effect of the basic research to such product development. If conflicts do arise, studying the reasons for the conflicts should lead to modifications to our advanced product development program, modifications to our basic research directions, or modifications to both.

However, basic research should affect a class of products, not just one. For each active advanced product development project, the analysis described in the preceding paragraph could be applied. For each planned advanced product development project, a simplified analysis based on this concept can be used. Finally, to access the value of a certain mix of research directions, an integration of the assessment of effects to all active and planned product development projects would be necessary. The proper integration of

these analyses into an overall strategic planning and management system for technology base activities is a potentially fruitful area of research that should be further investigated.

E. APPLICATION TO MANAGEMENT OF DOWNSTREAM UNCERTAINTIES

1. Downstream Uncertainties and Reliability Specification

Downstream uncertainties can be, to some extent, influenced by design choice; however, such uncertainties are not completely controllable by design since internal and external noises usually exist that will influence such uncertainties. This example considers the implications of uncertainty in product reliability (R).

Let R^o be the planned average reliability that the designers seek to achieve. This can be done, for example, by reducing parts count, selecting better quality parts, and providing better heat ventilation. However, the reliability actually realized in the field will also be influenced by other noises represented by ε_d, whose distribution is influenced by the choice of certain design parameters p. In functional form, we have

$$R^o = R^o(p) \ ; \ \pi(\varepsilon_d | p) \tag{5}$$

The reliability actually realized will be

$$R = R^o + \varepsilon_d \tag{6}$$

The total LCC for the product is

$$LCC = C_P(R^o(p)) + C_M(R) + C_S(R) \tag{7}$$

where

$C_P(R^o(p))$	is the product development cost
$C_M(R)$	is the total life cycle scheduled maintenance cost
$C_S(R)$	is the total life cycle service repair costs.

Let $p^*(R^*)$ be an optimizing solution of

$$\min_p \left\{ C_P\left(R^o(p)\right) + E\left\{ C_M\left(R^o(p)+\varepsilon_d\right) + C_R\left(R^o(p)+\varepsilon_d\right)\right\} \mid R^o(p) = R^* \right\} \tag{8}$$

Now we can rewrite (7) as

$$LCC(R^*,\varepsilon_d^*) = C_P(R^*) + C_M(R^*+\varepsilon_d^*) + C_R(R^*+\varepsilon_d^*) \tag{9}$$

where ε_d^* has distribution $\pi(\varepsilon_d^* | p^*(R^*))$. Thus the specification of R^*, the reliability level, does indirectly influence the downstream uncertainties.

In general, we will have the curves for the cost components as given by Figure IV-11, where $R = R^* + \varepsilon_d^*$. From the $C_P(R^*)$ curve, we see that

$$\frac{\partial C_p(R^*)}{\partial R^*} \geq 0 \;\; ; \;\; \frac{\partial^2 C_p(R^*)}{\partial R^{*2}} \geq 0 \tag{10}$$

However, from the $C_M(R) + C_S(R)$ curve, we see that

$$\frac{\partial\{C_M(R) + C_S(R)\}}{\partial R} \leq 0 \;\; ; \;\; \frac{\partial^2\{C_M(R) + C_S(R)\}}{\partial R^2} \geq 0 \tag{11}$$

Now if we take the expected value for LCC (R^*, ε_d^*) we have

$$\begin{aligned} LCC(R^*) &\triangleq \int LCC(R^*, \varepsilon_d^*)\, \pi\left(\varepsilon_d^* | p^*(R^*)\right) d\varepsilon_d^* \\ &= C_p(R^*) + \int \left\{C_M(R^* + \varepsilon_d^*) + C_S(R^* + \varepsilon_d^*)\right\} \pi(\varepsilon_d^* | p^*(R^*) d\varepsilon_d \end{aligned} \tag{12}$$

From (12) we see that $LCC(R^*)$ would have a general shape as given in Figure IV-12. The point R_1^* is the optimum reliability level to be specified. If R^* is specified as greater than R_1^*, then the marginal cost in improving reliability is higher than the reduction in maintenance and repair cost.

Suppose that the product under consideration is an equipment that is needed for continuous operation, and when an equipment is down for maintenance or repair, a spare one is needed to carry on the operation. Therefore, we may have an added availability requirement.

If we require that N^* equipments are always available, then we must have more than N equipments in place so that, on the average, we will have at least N^* equipments operational. We shall refer to the set of N equipments as a system. Our interest in this case is not the LCC for each equipment, but the LCC for the total system.

Let α be a fraction of time that an equipment is available for operation. The availability requirement can be represented by

$$\alpha N \geq N^* \;\; ; \;\; N = \text{total number of equipments in the system} \tag{13}$$

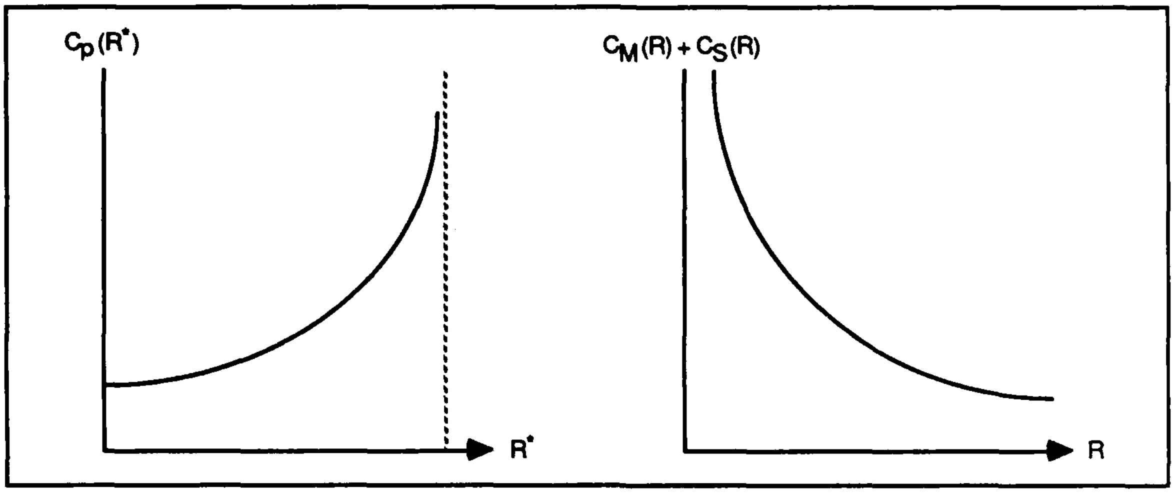


Figure IV-11. Cost Components of LCC

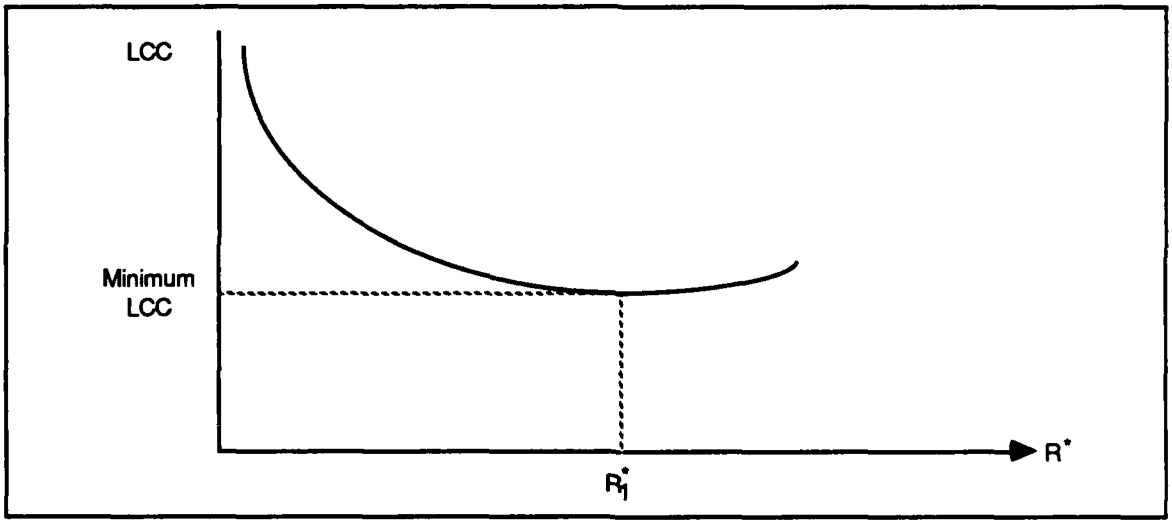


Figure IV-12. The LCC Curve

α is dependent on R, the actual reliability realized. If the first equipment issued is given a planned reliability R^*, how many should be purchased? This can be computed in a variety of ways; one possible approach is

$$\min_N E\left\{\left[\left(\alpha\,(R)\,N - N^*\right)\right]^2\right\} \tag{14}$$

where

$$\left(\alpha(R)N - N^*\right)^- = \begin{cases} o & \text{if } \alpha(R)N - N^* \geq 0 \\ \alpha(R)N - N^* & \text{otherwise} \end{cases} \tag{15}$$

Regardless of the specific method of finding N, as long as the method reflects our desire of ensuring (13), we have

$$N = N(R^*)$$

with the property

$$\frac{\partial N}{\partial R^*} \leq 0 \tag{16}$$

Now the LCC for the system is given by

$$LCC_S = N \bullet LCC \tag{17}$$

where LCC is the individual product life cycle cost. We thus have

$$\frac{\partial LCC_S}{\partial R^*} = \frac{\partial N}{\partial R^*} LCC + N \frac{\partial LCC}{\partial R^*} \tag{18}$$

Since $\frac{\partial N}{\partial R^*} \leq 0$, at the point R_1 where $\left.\frac{\partial LCC}{\partial R^*}\right|_{R^*=R_1} = 0$, we will still have $\left.\frac{\partial LCC_S}{\partial R^*}\right|_{R^*=R_1} \leq 0$. Thus, general shape of LCC_S as compared to LCC will be as shown in Figure IV-13. R_2 is the reliability level that is optimum for the system. R_2 is an increasing function in N^* and $R_2 > R_1$. The implication of this result is as follows--if we are considering the LCC of a system with a certain system operational requirement, then it pays to develop a product of a much higher reliability, even though the marginal cost in improving the reliability is higher than the marginal reduction in maintenance and repair cost for each product considered individually.

2. Uncertainty in Reliability and Parts Availability

Suppose that the design team must decide whether they should design the product based on standardized parts that are readily available or design the product by specifying the parts needed and ask certain vendors to manufacture those parts. If the second approach is used, we can specify the reliability level for the parts that will result in the

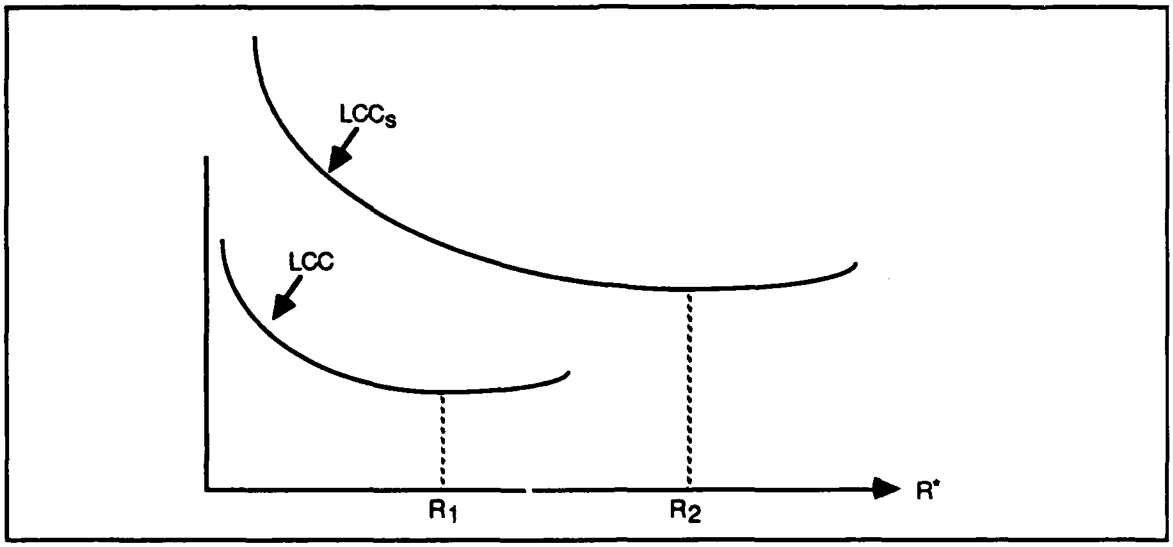


Figure IV-13. LCC $_S$ Curve as Compared to LCC Curve

optimum product reliability level as discussed in the preceding section. However, with the first approach, we have to accept whatever reliability level is offered by the suppliers.

In the first case, the LCC of the product does not depend on availability of parts but on only their reliability level. However, in the second case, where there is an availability constraint, parts availability plays an important role.

Let LCC_1 be the average life cycle cost if the first approach is used and LCC_2 is the average life cycle cost if the second approach is used. Let α_i be the fraction of time that an equipment is available for operation if the product is developed using the ith approach. The constraint is

$$\alpha_i N \geq N^* \qquad i = 1,2 \tag{19}$$

The fraction α_i depends on R_i and ι_i, where R_i is the parts reliability and ι_i is the lead time in parts availability if the ith approach is used. We have the property

$$\frac{\partial X_i}{\partial R_i} \geq 0 \qquad \frac{\partial \alpha_i}{\partial \iota_i} \leq 0 \tag{20}$$

Using the similar argument as in the last section, we see that the number of equipments purchased N will have the following properties:

$$\frac{\partial N}{\partial R_i^*} \leq 0 \qquad \frac{\partial N}{\partial \iota_i^*} \geq 0 \tag{21}$$

where R_i^* is the planned reliability and ι_i^* is the planned availability of parts if the ith approach is taken.

Suppose $LCC_1 > LCC_2$, $\alpha_1(R_1^*,0) < \alpha_2(R_2^*,0)$: i.e., if lead time in parts availability is zero, then option 2 is better than option 1. The plots for LCC_{S_i}, i=1,2, against ι will be as those shown in Figure IV-14. If $\pi_1(\iota)$, $\pi_2(\iota)$ are as given in Figure IV-14, then for the system LCC, option 2 is better. If, however, $\pi_2(\iota)$ is moved more to the right, option 1 is better. Since $\pi_1(\iota)$ is less controllable but $\pi_2(\iota)$ is more controllable, the issue is whether we can have effective control on the vendor in reducing lead time in parts delivery. In general, if a component has special features that are unique and are absolutely necessary, then standardized parts may not be that readily available, in which case, option 2 may be the better choice. The analysis indicates that, in this case, more emphasis should be devoted to tightening the relationship with the vendor selected to provide the component. On the other hand, if standardized components can be used, then most likely $\pi_1(\iota)$ will be clustered at low values of ι, which implies that option 1 may be a better choice. For a product with many component parts, this analysis can be used to determine which component parts should be obtained from standardized markets and which parts from custom or semi-custom markets. Such a determination will provide a guideline for product design.

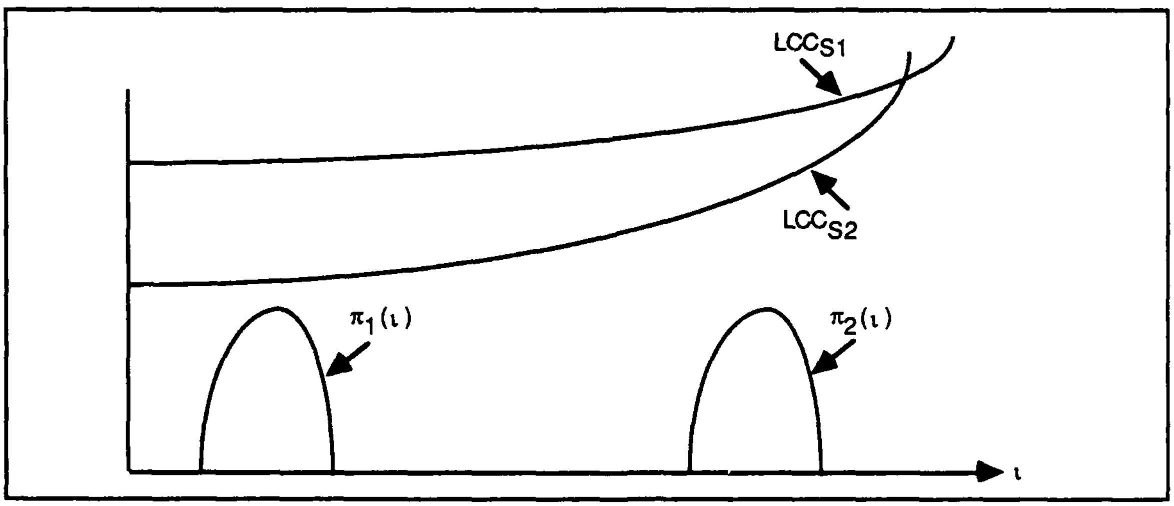


Figure IV-14. System Life Cycle Cost as a Function of ι

V. DECISION SUPPORT SYSTEM REQUIREMENTS

A. MANAGEMENT STRUCTURE TO SUPPORT OVERLAPPING PROCESS

A management structure that is appropriate for problem solving in the overlapping paradigm is illustrated in Figure V-1. Each functional group is responsible for problem solving in a specific phase. The functional groups may be formed in a dynamic manner--over time, members in group i may change and the mission in each group may change in response to exogenous events. The manager must accomplish the following:

- Identify phases and organize functional groups, in a dynamic manner, in line with these phases. Team stability and functional optimality must be considered.
- Once the functional groups are organized, determine the starting time for each phase in real time and provide guidelines in setting the degree of flexibility at the beginning of the phase.
- Monitor and coordinate consensus seeking among functional groups to manage the reduction of flexibility in the funnel process in each phase.

Each functional group has similar problem solving characteristics, even though each group uses different tools and methods in solving its assigned problem. The common goals are

- Focus on generating appropriate options with flexibility when ambiguity is large. Since there is a cost incurred in generating each option, the team must trade off this cost with the degree of flexibility.
- Focus on optimizing the product when ambiguity has been reduced to a level so low that it has been practically eliminated.
- Frequently communicate with team members in the upstream and downstream phases while work is in progress. Provide review of decisions about to be made by upstream members and provide suggestions for a better overall solution. When conflicts arise, exchange points of view to achieve consensus.

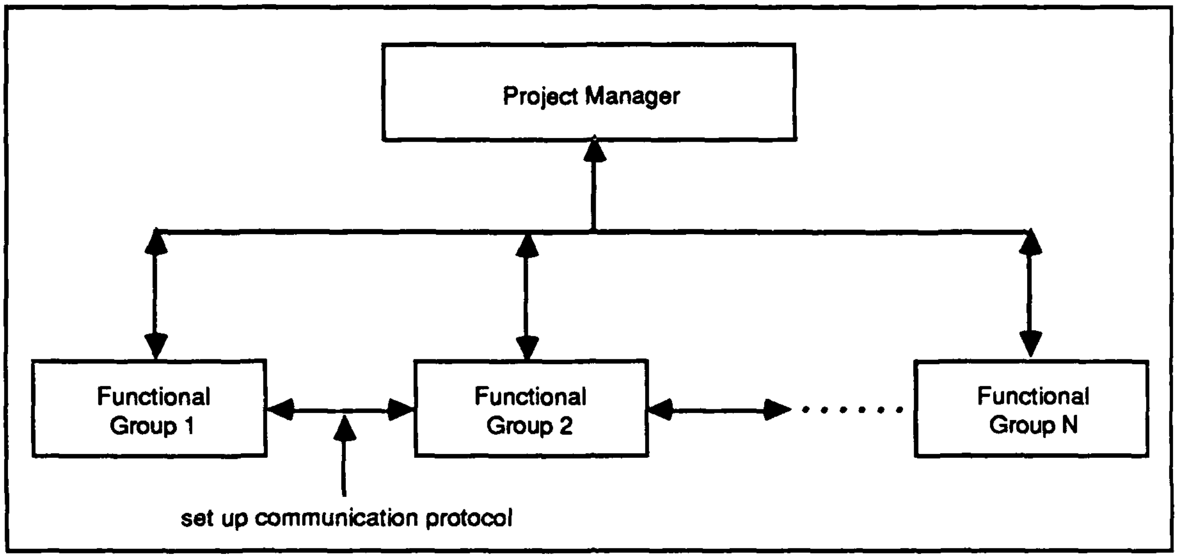


Figure V-1. Management Structure for Overlapping Paradigm

While both the manager and the functional groups are involved in the consensus seeking process, their roles will differ. Whatever consensus among different groups is reached, it is important that all of the functional group members also agree--consensus should be reached, by and large, among the functional groups. The manager should guide the consensus seeking process. For example, the manager may emphasize a sense of time urgency, communicate the relative trade-offs among the three process attributes, and suggest new ways to solve conflicts.

B. DECISION SUPPORT SYSTEMS FOR UNCERTAINTY MANAGEMENT

Many of the current research activities in ULCE are driven primarily by the technology point of view--how sophisticated AI and distributed processing technology can be used to develop a complex, distributed, knowledge-based system that helps to integrate design and manufacturing. The approaches centers on the notion that a decision in the upstream (design) phase may severely restrict downstream (manufacturing) options. Therefore, the implications of upstream decisionmaking on downstream restrictions should be considered. If the choice imposes too many restrictions on the downstream phase, the upstream team member should be alerted or the upstream team should be prohibited from making such a choice. The technology solution advanced to achieve this is to develop a

large and complex knowledge-based system that captures all of the relevant downstream problem solving knowledge. The emphasis is on "intelligent" information management.

While this technology solution seems acceptable, it does not address the basic issues that any product development process faces--management of risks and uncertainties. Competitive pressure imposes a greater demand on us to deal with these issues more effectively. We believe that an overlapping development approach in which risk is effectively managed offers the most promising appoach to ULCE implementation.

The overlapping approach has been adopted in many design activities. However, the overlapping approach will introduce upstream and downstream uncertainties (as discussed in Chapter II), which implies that an appropriate solution for dealing with an overlapping process must deal with such uncertainties directly. Unfortunately, most of the current methods adopted for the overlapping approach in design are primarily deterministic methods [Ref. 1 and Ref. 12]. At best, only downstream uncertainties are considered [Ref. 4]. Thus, decision support systems that support conventional solution methods in solving problems in the overlapping approach may only help us to derive an unfavorable solution faster.

An appropriate computer environment that supports ULCE must support the appropriate risk management process. We shall refer to such a computer system as a ULCE environment. A ULCE environment must be compatible with a management structure that is appropriate for problem solving in the overlapping paradigm. Under this paradigm there are different functional groups, each responsible for problem solving in a specific phase. These functional groups are formed in a dynamic manner. Over time, members in a group may change and the mission in each group may change in response to exogenous events. The manager must identify different phases, organize functional groups in a dynamic manner in line with these phases, and determine the ordering and the starting time of each phase. We shall refer to these as management control activities. Such activities initiate a subprocess to be carried out by a certain functional group. The determination of such control activities is not based on rigorous analysis but rather on creativity, heuristics, and experience. For example, the discussions in Chapter IV deal with the evolving phases based on heuristic arguments.

Once a functional group begins its activities, the members must generate flexible options. The appropriate choices among these options are made by integrating upstream and downstream risk analysis. While the generation of options is based on the members'

creativity, heuristics, and experience, the risk analysis discussions in Chapter IV can provide an analytical base for the choice of options. The manager handles the risk by monitoring and coordinating consensus seeking among functional groups to control the reduction of flexibility in the funnel process in each phase. Chapter IV provides foundations for such control activities. Note that creativity, heuristics, knowledge, experience, and mathematical analysis are used to support such control actions.

Communication among all team members in the upstream and downstream phases is crucial so that downstream analysis can help provide better upstream decisions. Moreover, good communications allow the team members to bring out potential conflicts and try to resolve them as soon as possible. Because communication among team members is essential, an appropriate networking hardware architecture will be required--even the digital transmission of output from one team to another team will increase overall productivity. To support the team problem process in product development, we propose a networking of workstations as illustrated in Figure V-2.

The manager workstation supports the three basic activities--monitoring development status, management control and coordination, and performing analysis to justify decisions. How these activities are carried out depends on the manager's working style.

Monitoring continuous activities is not merely reviewing all the updated status information; monitoring implies a continuous assessment of the development status--what options have been generated by each team, when convergence has started to take place in each phase and how fast is it occurring, how each team is progressing according to the plan, and whether conflict has arisen. Monitoring will require transformation of accumulated data into certain indicator variables that can represent the development status. The data can be in symbolic as well as numeric form, as can the indicator variables. The transformation can be by symbolic manipulation or by a mathematical model.

The values of the indicator variables will trigger proper management control and coordination activities. The triggering mechanism can be based on rule-based reasoning for frequently recurring situations. For exceptional situations, the manager must be involved in determining the control action, which may require some analysis. What analysis should be performed and how it should be performed are the basic issues in these situations. To

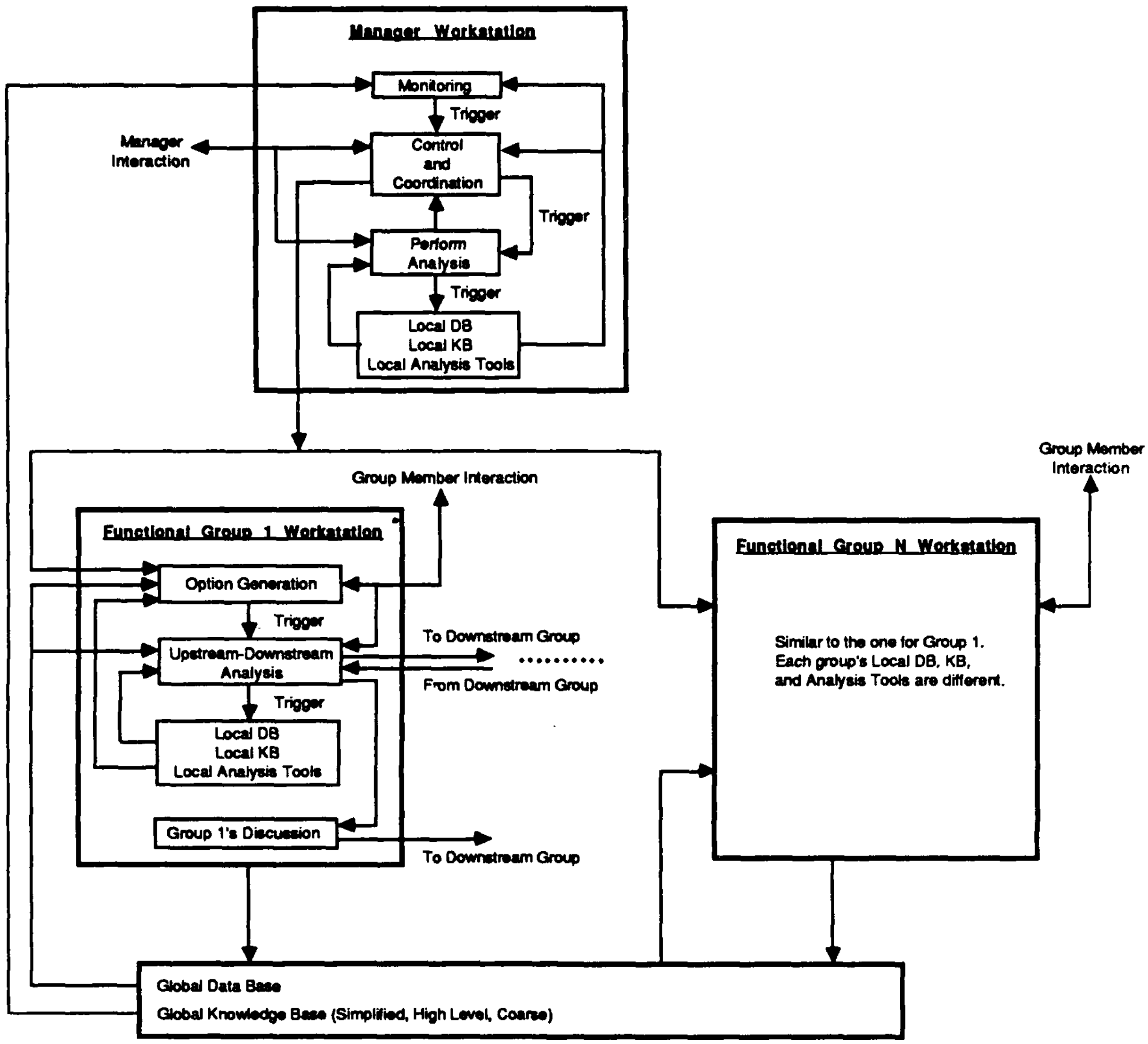


Figure V-2. ULCE Environment

support such activities, a model, construction, and editing environment to support the analysis, problem formulation activities, and reconfigurability of the tools in the tool-set tailored to the specific analysis requirements will be needed.

An individual functional group's activity in arriving at a certain decision is triggered by management control instruction. In beginning a decision process, group members will search for options or alternatives based on what is instructed and what is known. Such a process can be based on a rule-based reasoning for common, recurring situations or based on the members' creativity. Once an option is generated, it is then evaluated. This triggers

an analysis based on upstream-downstream integration as discussed in the previous chapter. Such an analysis requires the members to construct an analysis model and pick an appropriate analytical tool to solve the analysis. The analytical tools will likely be based on CAD/CAM, statistical, optimization, simulation, and search methods. Therefore, to support the group members, the group workstation must also have a model, construction, and editing environment and reconfigurability of a subset of analytical tools (CAD/CAM, statistical, simulation, optimization, etc.) tailored to the specific model formulated. Note that most of the proposed systems that support ULCE are designed to facilitate the downstream integration. To integrate this with upstream analysis, an analysis process, as discussed in the last chapter, must be incorporated.

The output of each group's decisions goes to the functional group for the next phase as well as to the global data base, which is monitored by the monitor. The decision being made in each phase is dynamically changing. For example, for the designer group, the decision at any time can relate to the set of design options being considered, the degree of flexibility in the design process, etc.

A coarse global knowledge base should be used to capture the most common knowledge relevant to the development process. Such a knowledge base should be simple and can be used in coming up with first-order analysis and recommendations. A more detailed domain knowledge base is captured in individual local knowledge bases embedded in each functional group's workstation. Each local knowledge base will be different and can only capture the most relevant knowledge for the specific group's activities. Additional knowledge (usually new knowledge) will be provided by group members.

Because of rapid advancements in technological innovation, the life cycle of knowledge will be short. Thus, the knowledge base must be constantly updated or modified to represent the latest knowledge of the situation. Therefore, easy rule editing and rule maintenance capabilities are absolutely necessary for knowledge-based technology to be useful in high technology product development processes.

VI. SUMMARY AND RECOMMENDATIONS

A. SUMMARY

This paper describes a framework that addresses the risk management issue in the new product development process. An overlapping paradigm for the development process is proposed, which creates a new risk management problem. This new problem is dealing with upstream and downstream uncertainties, and the required management process is coordinating upstream and downstream analysis to control the reduction of upstream uncertainty so as to converge to a point design. A method for integrating the upstream and downstream analysis has been developed based on development of a generalized loss function to deal with downstream uncertainty and then using the downstream results in a subsequent upstream analysis.

An analytic framework for consideration of issues such as staging of the various phases of a development project was also developed and discussed in the context of problems such as concurrent engineering and science and technology program planning and management.

Finally, we described a ULCE environment to support a high technology product development process. The main focus is on the architecture of such an environment and the functional capabilities that such an environment should have, and not on the detailed hardware-software system specifications and designs.

It should be emphasized that the research reported here is focused on providing a foundation that allows us to address ULCE properly from a risk management perspective. Given increasing competitive pressures, it is becoming more important that we learn how to develop products using the most recent technology in a timely manner to meet user needs, while keeping life cycle cost low. This demands far more attention to risk management throughout the process. Unfortunately, this issue has been rarely addressed in the vast array of research activities focused on product design and manufacturing.

Our contribution is a broad treatment of such issues and development of a foundation for further research activities. For example, the discussion of the generalized loss function approach to managing downstream uncertainties provides a solution method at a conceptual level only. To implement the method, we need to describe how to develop the response model, the model for the downstream uncertainties, and the optimization methods that will be required. In practice, the construction of such models is the major difficulty. In many cases, analytical form for such models may not be obtainable, which prohibits straightforward application of standard optimization methods.

The second difficulty is the assessment of uncertainties in deriving the loss function. Such assessment may be done by extracting experts' opinions in common situations or using a Monte Carlo simulation method. Different types of difficulties are associated with these two approaches--the first approach requires converting expert knowledge into an appropriate distribution; the second problem requires choosing the right level of model aggregation with an appropriate model error representation.

B. RECOMMENDATIONS FOR FURTHER RESEARCH AND DEVELOPMENT

1. Evaluation of the Generalized Loss Function

In this research, we have developed the concept of the generalized loss function, which balances life cycle cost with quality lost due to deviation achievement of physical requirements ($J^*(\varepsilon_u)$ as derived in Chapter IV). Such a function plays a major role in the entire risk management process. Thus the success or failure of implementing the method discussed in this paper hinges on being able to derive or approximate $J^*(\varepsilon_u)$.

The evaluation of $J^*(\varepsilon_u)$ requires two optimization problems (equations (2) and (3) in Chapter IV). The difficulties of solving these optimization problems are discussed in the preceding section. Research on a methodology to solve these optimization problems, which in many situations cannot be represented in analytical form, is urgently needed.

Taguchi suggested certain statistical methods [Refs. 6, 7] using experimental design in solving one of the two optimization problems (equation 2). However, the method proposed by Taguchi may be computationally prohibitive when dealing with a complex design problem where there are many design parameters to be selected. Orthogonal array

experimentation methods [Ref. 7] do not use experts' knowledge, and for complex design problems, a more intelligent method of pursuing experiments may be needed.

We feel that an approach that extends the current Taguchi method to deal with the two optimization problems presented here while integrating some expert systems technology may provide a practical method in evaluation of $J^*(\varepsilon_u)$.

2. Assessment of Requirements Ambiguity Based on Perceived Need

The next critical function that is needed to perform risk management is the requirements specification ambiguity $\pi(\varepsilon_u)$. This function is assessed in the beginning of the design process based on some unclear notions of how the product should be used. Note that this is not a statistical uncertainty but rather a reflection of the limits of our knowledge of how meeting certain design requirements will lead to a product that meets the user's needs. Syed and Tse [Ref. 13] have developed an approach in which expert's knowledge and market data are integrated via a pairwise comparison method to relate how certain product attributes can meet the needs of certain market segments. While the exact method may not be transferable, some of the basic concepts employed by Syed and Tse can be applied to this situation.

3. Design Concept Evaluation--Integrating Requirements Ambiguity and the Generalized Loss Function Approach for Downstream Uncertainty

Integrating requirements ambiguity and the generalized loss function approach is conceptually rather straightforward (as described in Chapter IV); however, practical implementation is difficult. Note that the integration hinges on generating the two functions $\pi(\varepsilon_u)$ and $J^*(\varepsilon_u)$, for $\varepsilon_u \in \Omega$. With Ω a continuous parameter set, the generation of these two functions for all parameters will be totally impractical. We need a methodology to allow us to approximately evaluate the design concept as discussed in Chapter IV without requiring evaluation of $J^*(\varepsilon_u)$ and $\pi(\varepsilon_u)$ for *all* $\varepsilon_u \in \Omega$.

4. Managing the Dynamic Reduction of Upstream Ambiguity

One cycle of the downstream and upstream integration results in either a reduction of requirements ambiguity or identification of a potential conflict situation. Management must determine how to further reduce the requirements ambiguity in the first situation and how to resolve conflict when the second situation arises. The solution for both

management issues hinges on exploring the effective use of resources to carry out certain activities that will modify or refine the assessments on $\pi(\varepsilon_u)$ and $J^*(\varepsilon_u)$. For example, a better understanding of the needs and how they can be satisfied will narrow $\pi(\varepsilon_u)$ and/or shift $\pi(\varepsilon_u)$. Such understanding can also lead to modification of the requirements space (new attributes introduced or some attribute made irrelevant).

Ways to modify or refine $J^*(\varepsilon_u)$ can include

- Refining certain parts of the system modeling
- Choosing different components
- Building a better vendor relationship
- Adopting a different maintenance strategy.

Note that in influencing $J^*(\varepsilon_u)$, we may have to engage in new activities now (such as more accurate modeling) or plan to engage in future activities (such as change maintenance strategy).

The manager thus faces a host of options from which to choose to continue the reduction of requirements uncertainties in some optimum manner or try to resolve potential conflicts. Each of these activities requires resources in terms of dollars, man-hours, and time. Thus the problem is one of resource allocation so that

- The project can be finished according to schedule,
- The development cost is within budget, and
- The available resources are optimally used.

This resource allocation problem is non-standard since all possible options are not specified a priori. Rather, the generation of new options may result from an assessment of the solution of an old resource allocation problem and exploring how combinations of certain activities will influence $J^*(\varepsilon_u)$ and $\pi(\varepsilon_u)$.

While the option generation process is based on heuristics and past experience, evaluation of the resource allocation process should be based on cost-benefit analysis. The top-level management process is based on a sequence of option/evaluation subprocesses. We believe that an integration of AI and operations research will facilitate an appropriate solution to this problem.

5. Demonstration of Applicability of the Methodology to Specific Classes of Problems via Real Cases

Since the development process and the proposed method are different from the conventional practice, before one can develop some of the heuristics discussed in this section, one needs to accumulate working experiences by applying the methodology to specific classes of product development problems. Another objective of such application is to demonstrate the usefulness of the methodology. We propose to select real application cases, which by themselves are topics of significant importance.

Some of these application problems include managing the contracting process, product identification and development, concurrent engineering in high technology product development, and planning of an S&T program in conjunction with advanced weapons development.

6. ULCE Decision Support Environment

To support the implementation process, we need to develop a ULCE environment that can support the manager in controlling dynamic reduction in the requirements ambiguity and the functional groups in integrating the downstream and upstream analysis process when a specific ambiguity level is provided by the manager. Individual decision support systems are currently being developed for supporting certain specific functional group activities (for example, CAD/CAM). Ignoring all of the existing systems and redeveloping a new unified ULCE environment from scrap is impractical. Therefore, research on how to integrate and evolve the current systems to the target ULCE environment is the major challenge. We believe that this requires, first, a thorough understanding of the workings of the overlapping process as well as how the management issues arising from such processes can be addressed and solved effectively before the proper ULCE decision support environment can be designed.

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